Proton radius experiment at MESA

elastic electron-proton scattering at MAGIX

Sören Schlimme
Institute for Nuclear Physics
Johannes Gutenberg University Mainz

PREN2022 Convention:

International STRONG-2020 Workshop on the Proton Charge Radius and related topics

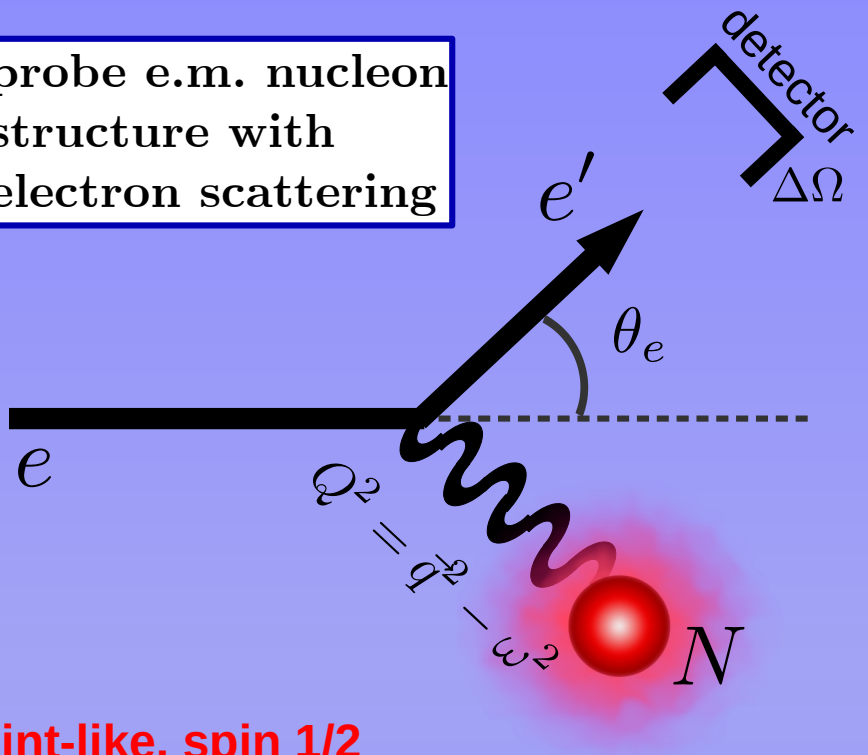
June 20-23, 2022, Paris, France

Cluster of Excellence PRISMA+

- Jet Target
- MESA accelerator
- MAGIX Spectrometer Setup
- Proton Form Factor Measurements

Elastic eN-scattering

probe e.m. nucleon structure with electron scattering



point-like, spin 1/2

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_e}\right) = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_e}\right)_{\mathrm{Mott}^*} \cdot \left(1 + 2\tau \tan^2 \frac{\theta_e}{2}\right)$$

substructure, spin 1/2 (e.g., proton, neutron)

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_e}\right) = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_e}\right)_{\mathrm{Mott}^*} \cdot \frac{1}{(1+\tau)} \left[G_{\mathrm{E}}^2(Q^2) + \frac{\tau}{\epsilon} G_{\mathrm{M}}^2(Q^2)\right]$$

$G_{\mathrm{E}}^2(Q^2) \leftrightarrow$ charge distribution

$G_{\mathrm{M}}^2(Q^2) \leftrightarrow$ magnetization distribution

Elastic eN-scattering

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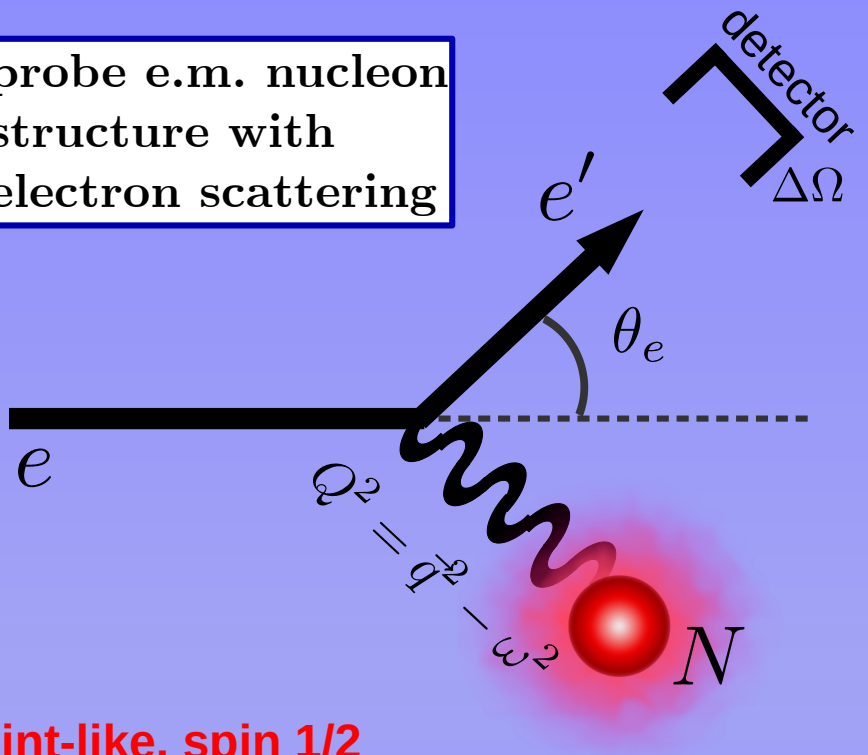

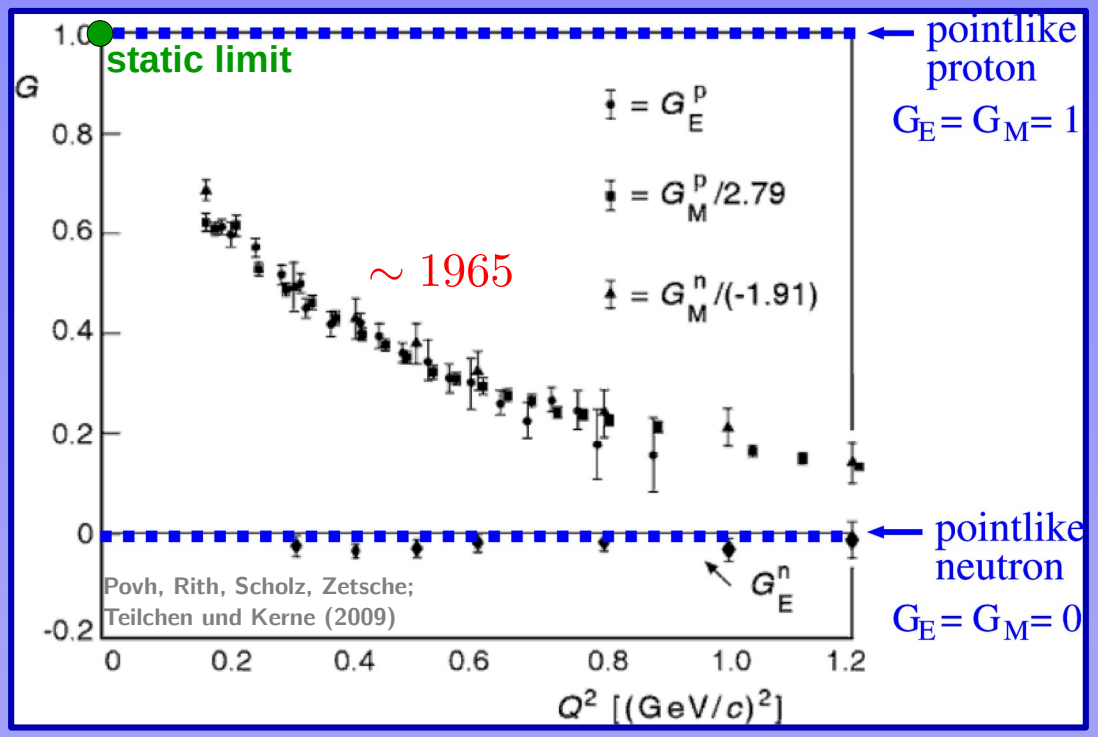

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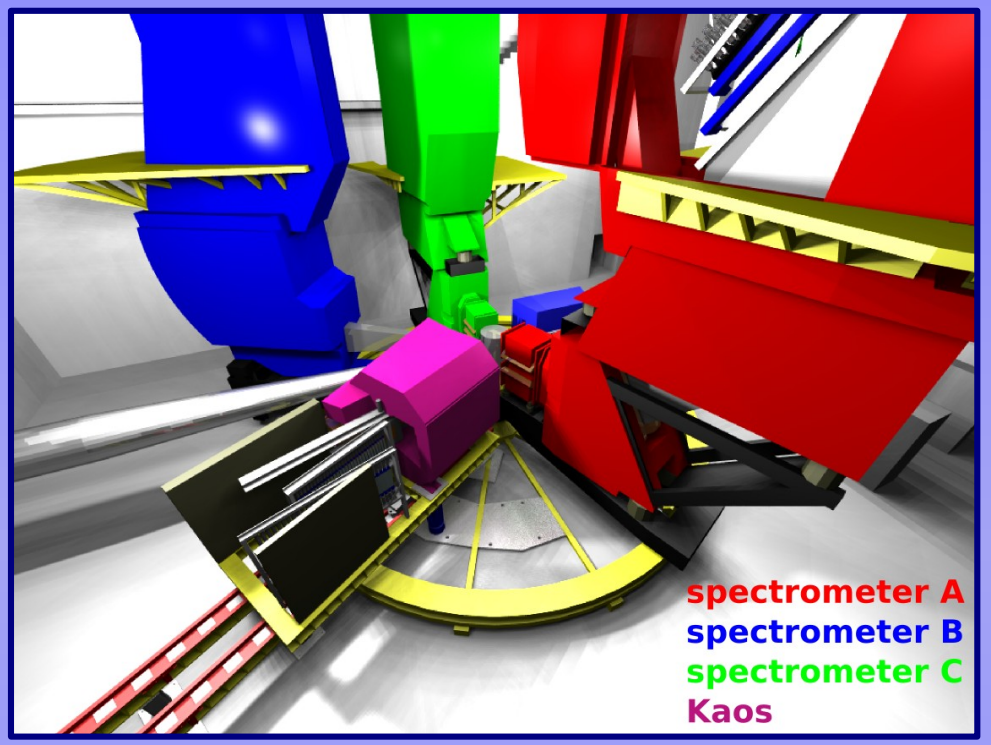
radius from slope: $\left\langle r_{\mathrm{E}}^2 \right\rangle = -6\hbar^2 \left.\frac{\mathrm{d}G_{\mathrm{E}}}{\mathrm{d}Q^2}\right|_{Q^2=0}$

Nucleon form factor measurements in Mainz



two PhD students you shall be

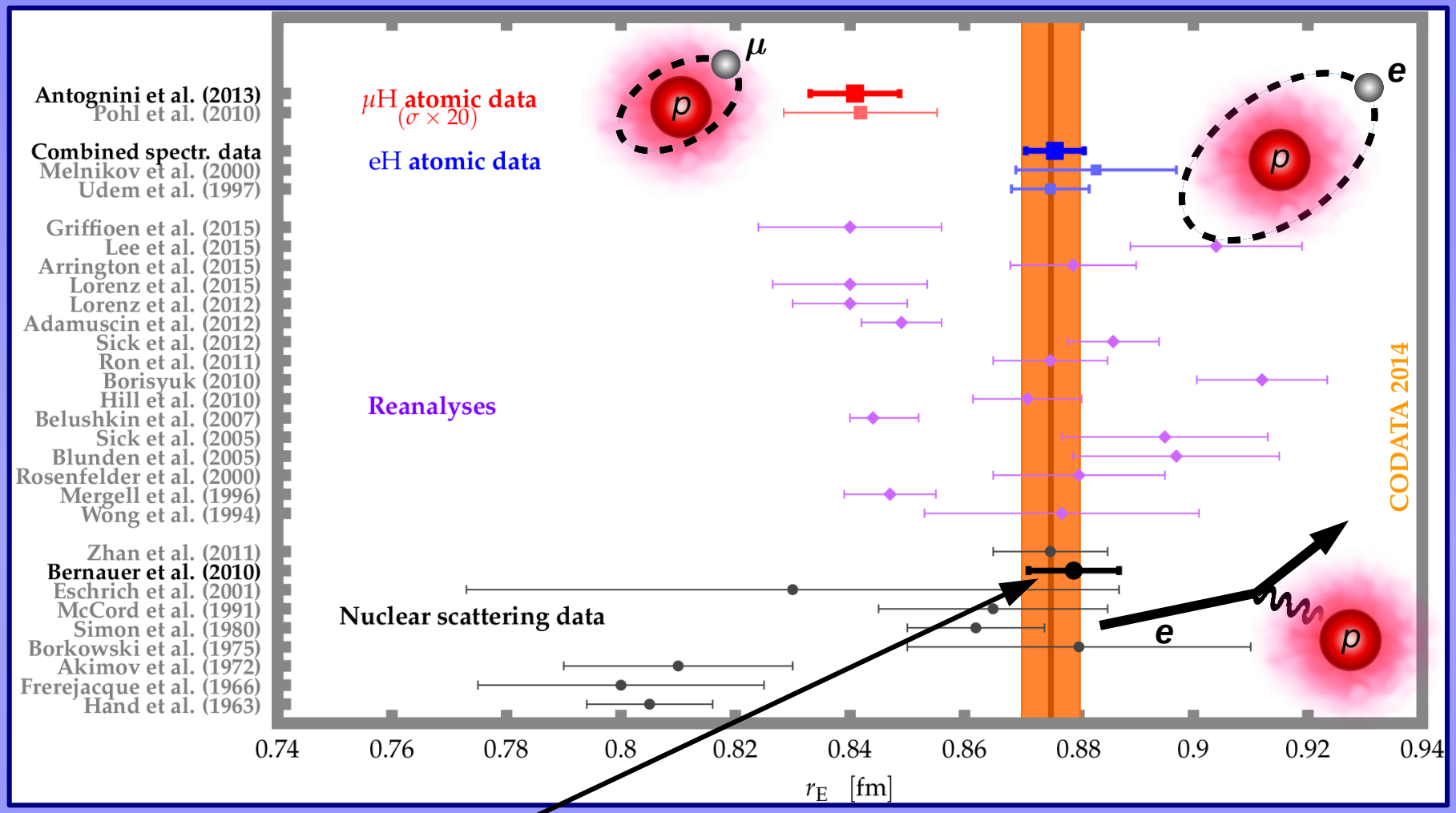
Previous Measurements at **A1-MAMI, Mainz University** (selection)**:**

G_E^p, G_M^p
1422 data points, Q^2 = **0.004 - 1 GeV²**
statistical errors below **0.2 %**
Bernauer *et al.*, PRL 105 (2010) 242001

G_E^n / G_M^n
1 data point, Q^2 = **1.58 GeV²**
statistical error: **23 %**
Schlimme *et al.*, PRL 111 (2013) 132504

The proton radius puzzle

SELECTED RESULTS ~2015



G_E^p, G_M^p

1422 data points, Q^2 = **0.004 - 1 GeV²**

statistical errors below **0.2 %**

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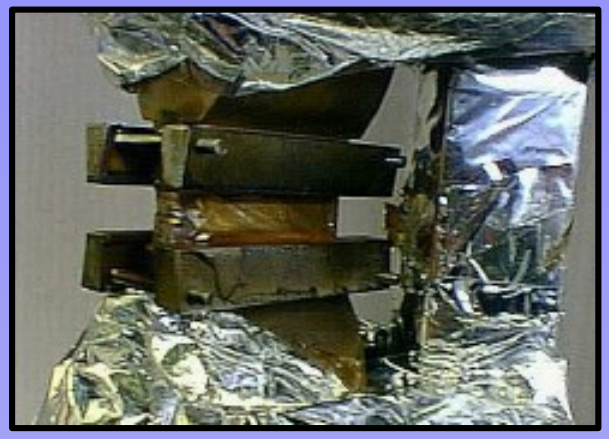
unconsidered effects, new physics, experimental errors ?!

call for dedicated, improved data!

Possible improvements in Mainz

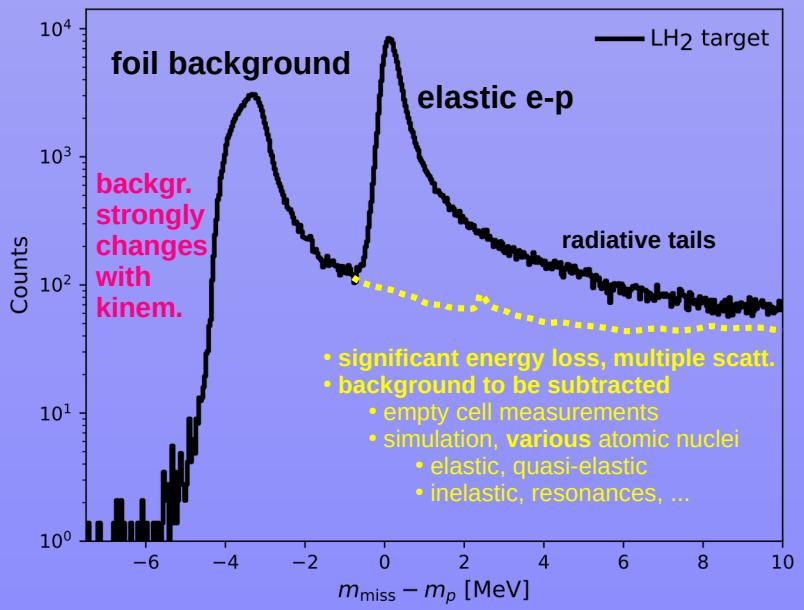
Experiment
with reduced experimental background



Havar foil

Element	Content (%)
Cobalt, Co	41-44
Chromium, Cr	19-21
Nickel, Ni	12-14
Tungsten, W	2.3-3.3
Molybdenum, Mo	2-2.8
Manganese, Mn	1.35-1.8
Carbon, C	0.17-0.23
Beryllium, Be	0.02-0.06
Iron, Fe	Balance

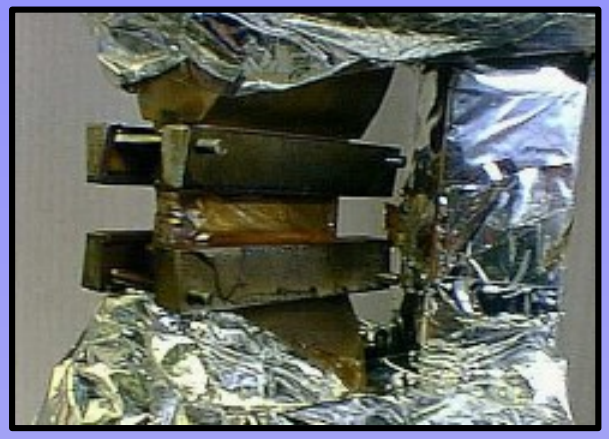
Liquid hydrogen target, in target cell



Possible improvements in Mainz

Experiment

with reduced experimental background **at reduced momentum transfer Q^2**



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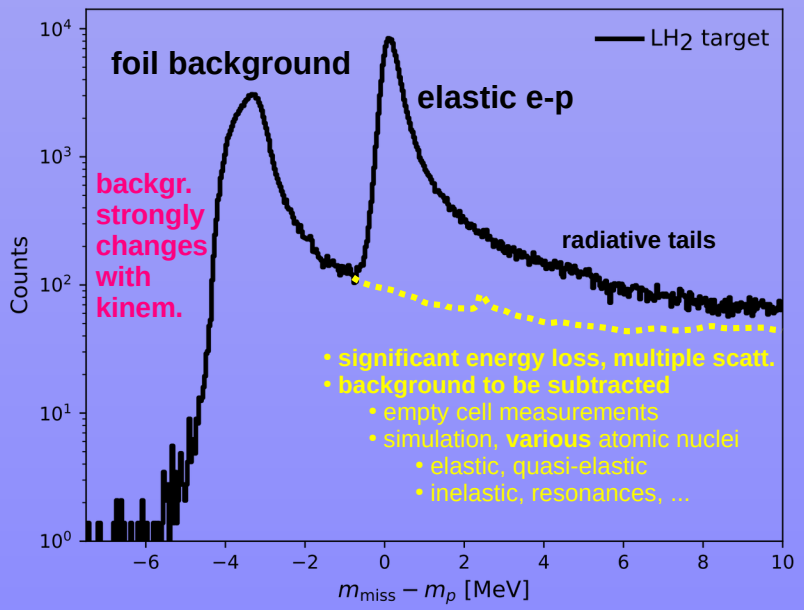

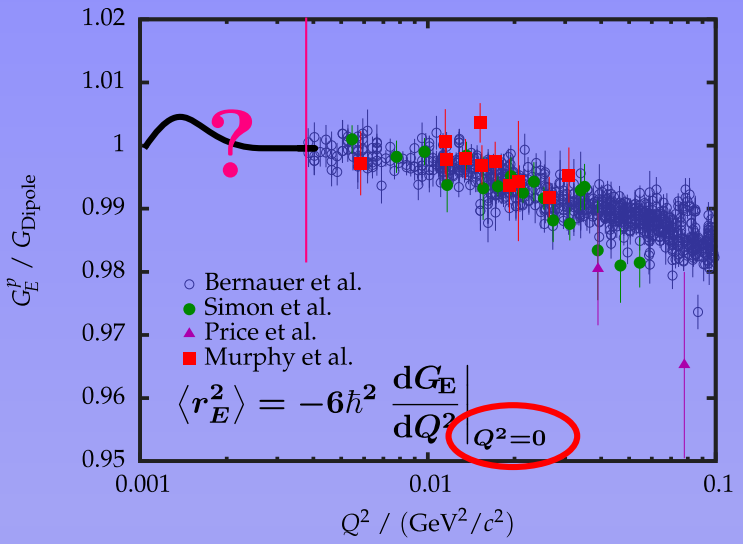

Possible improvements in Mainz

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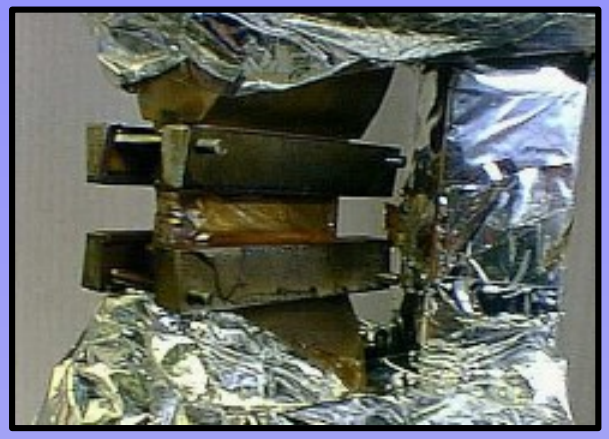

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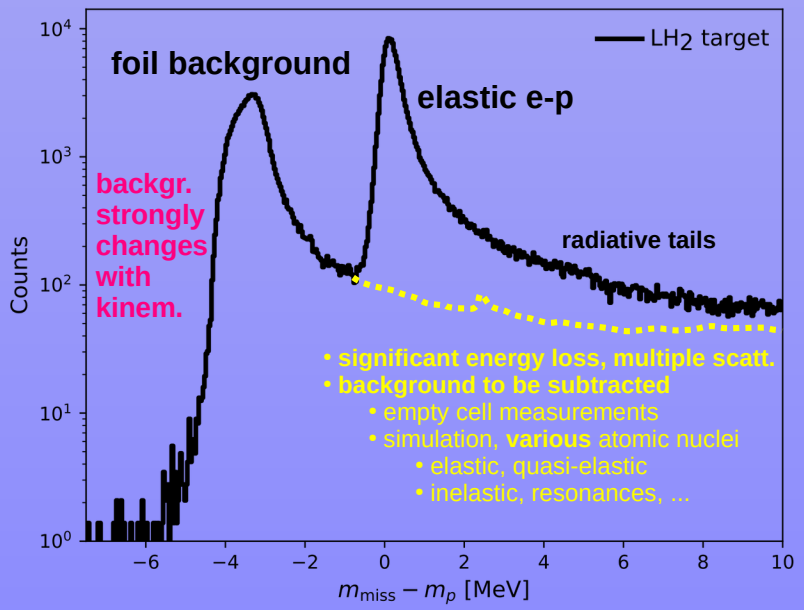
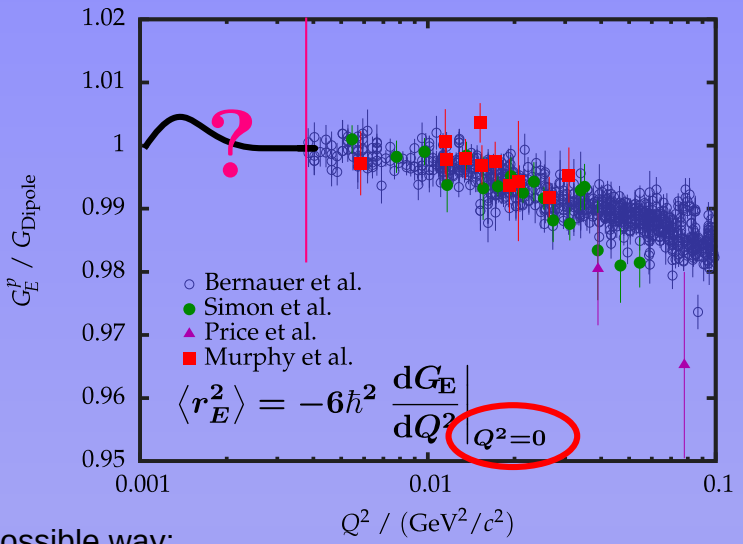
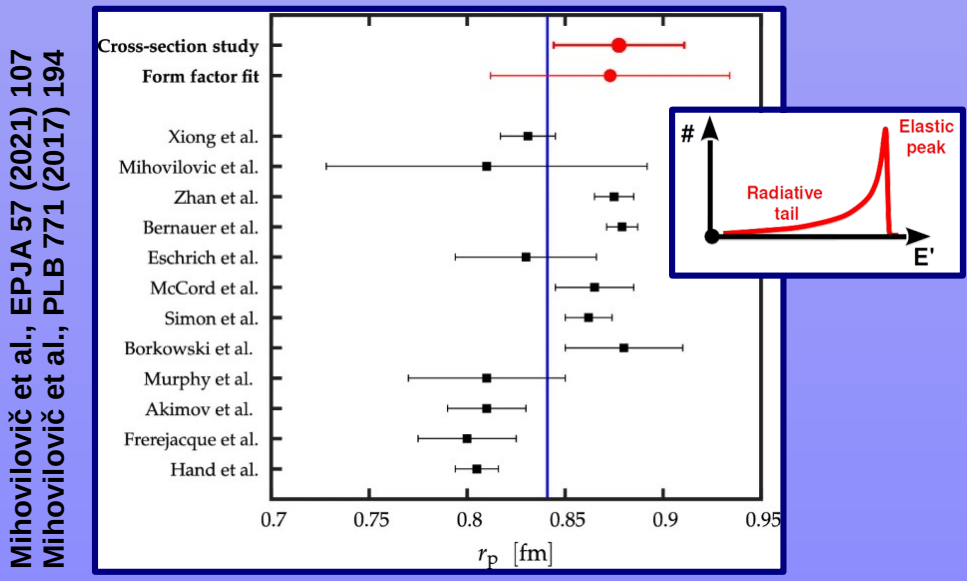




one possible way:

Initial State Radiation experiment:



Possible improvements in Mainz

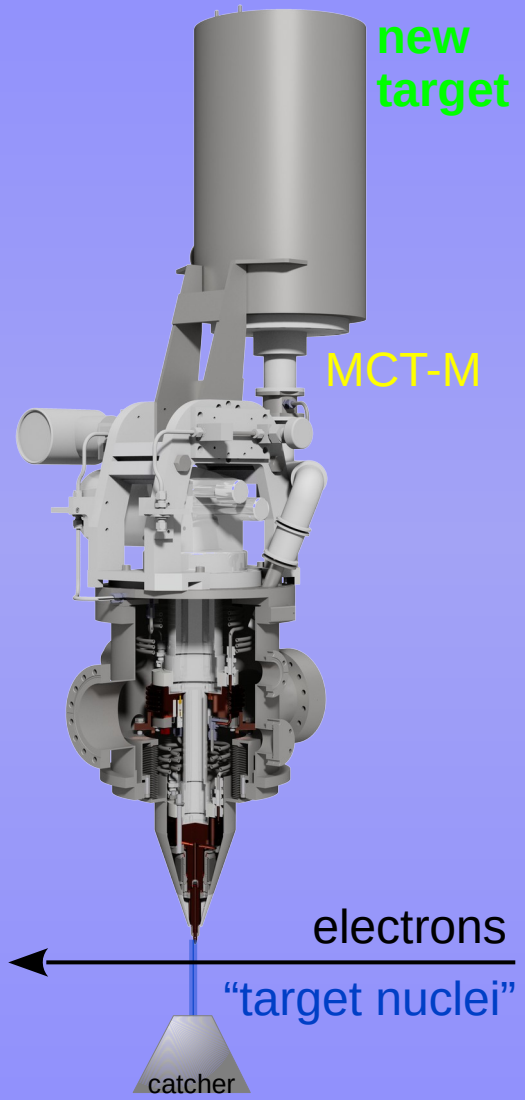
Experiment
with reduced experimental background **at reduced momentum transfer Q^2**

A new **low-energy, high-intensity electron accelerator** is currently being built
for measurements of the **proton form factors** at low momentum transfer
→ **proton radius**

Possible improvements in Mainz

Experiment

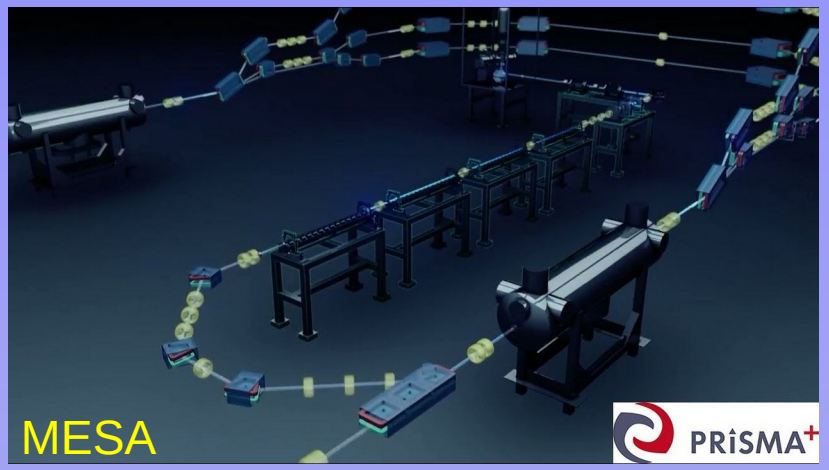
with reduced experimental background **at reduced momentum transfer Q^2**



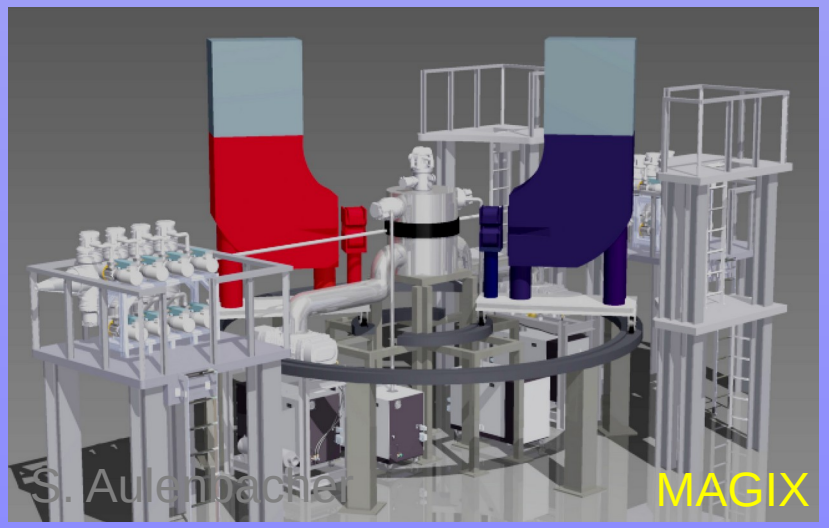
D. Bonaventura

for measurements of the
proton form factors

new
accelerator



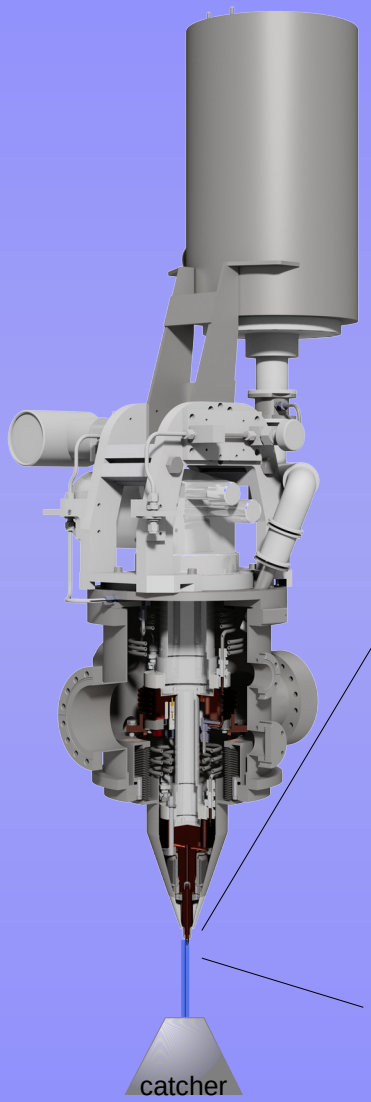
new
electron scattering experiment



Internal / injection target

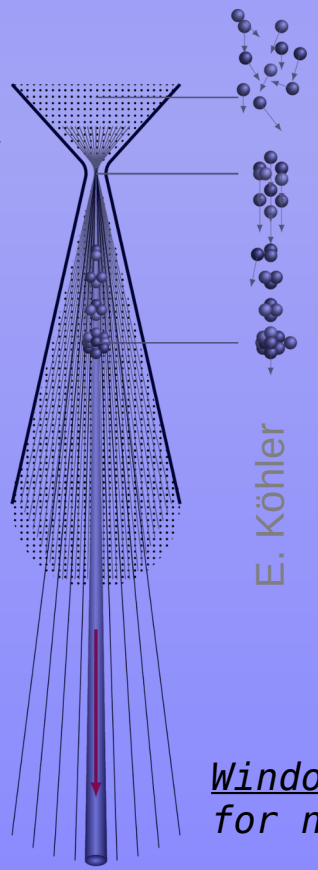
```
Name: ..................................... MCT-M
Type: ................ Cryogenic Gas Jet Target
Developer: .............. AG Khoukaz / Münster
Height: ................................... 1.43m
Operating material: ....................... gases
Operating temperature (hydrogen): ....... 40 K
Maximum gas flow (hydrogen): ........ 2400 l/h
Age: ...................................... 5y
```

S. Grieser *et al.*, NIM A 906 (2018) 120



D. Bonaventura

supersonic gas jet



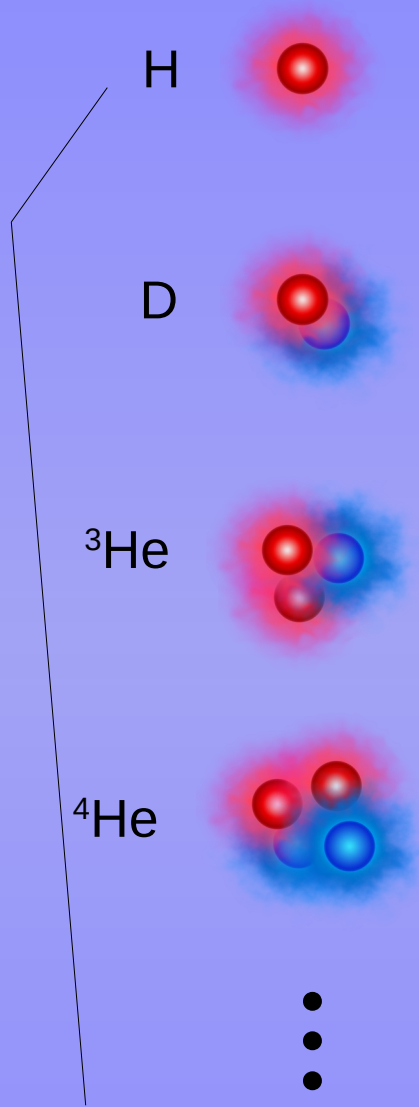
E. Köhler

convergent inlet zone

Laval nozzle

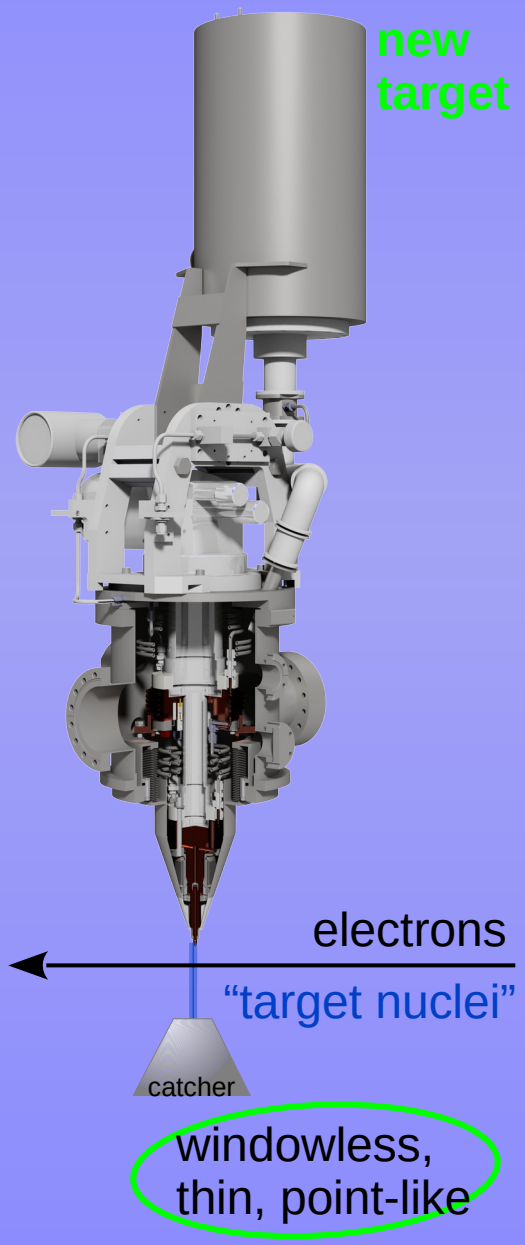
divergent outlet zone

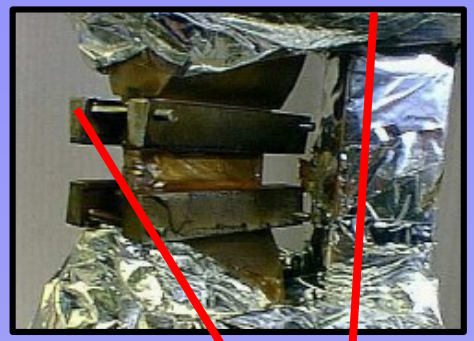
Windowless, thin, point-like target for nuclear physics experiments



gaseous targets up to **~Xenon**

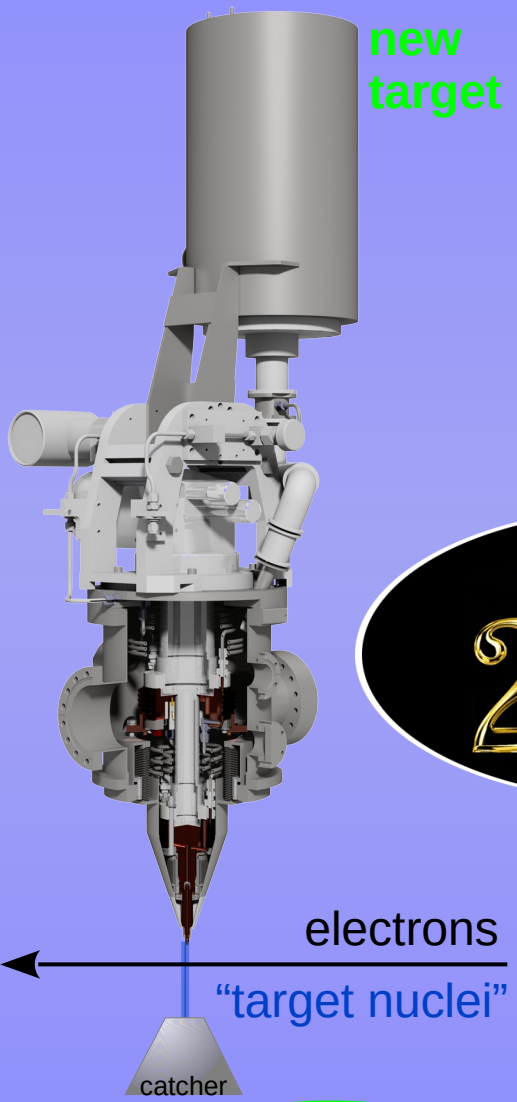
Internal / injection target

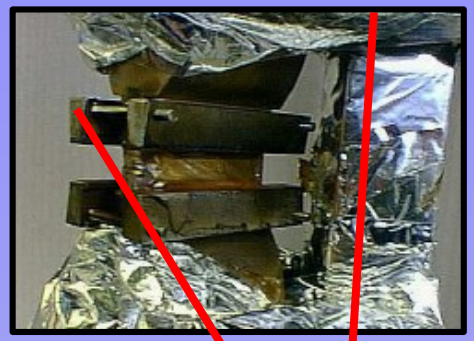




- large energy loss and multiple scattering
- background from target foils
  - empty cell measurements
    - not the same Eloss, multi scatt
    - not for all settings ep experiment
      - background model
- background from (thin) ice layer
- spectra distorted by (thin) ice layer
- rescattering on thick frame
- target length acceptance issues

Internal / injection target





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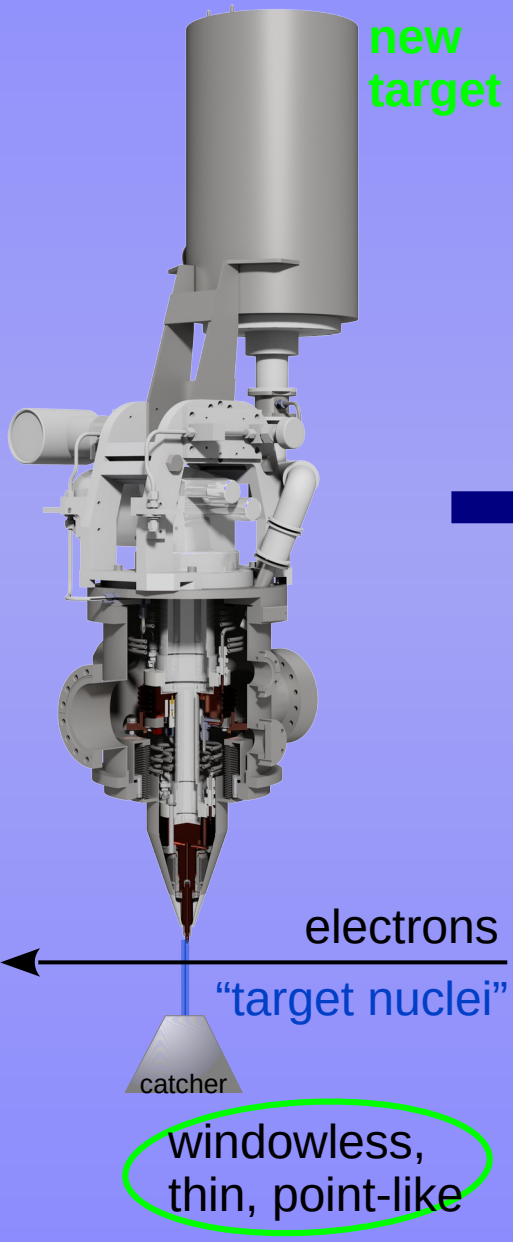
The MAGIX jet target at A1



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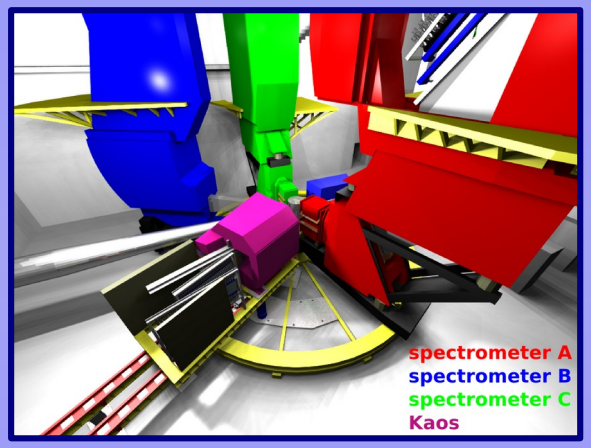

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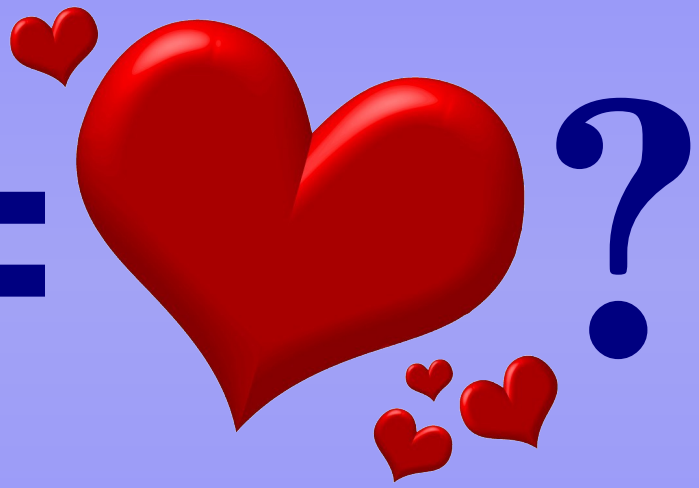

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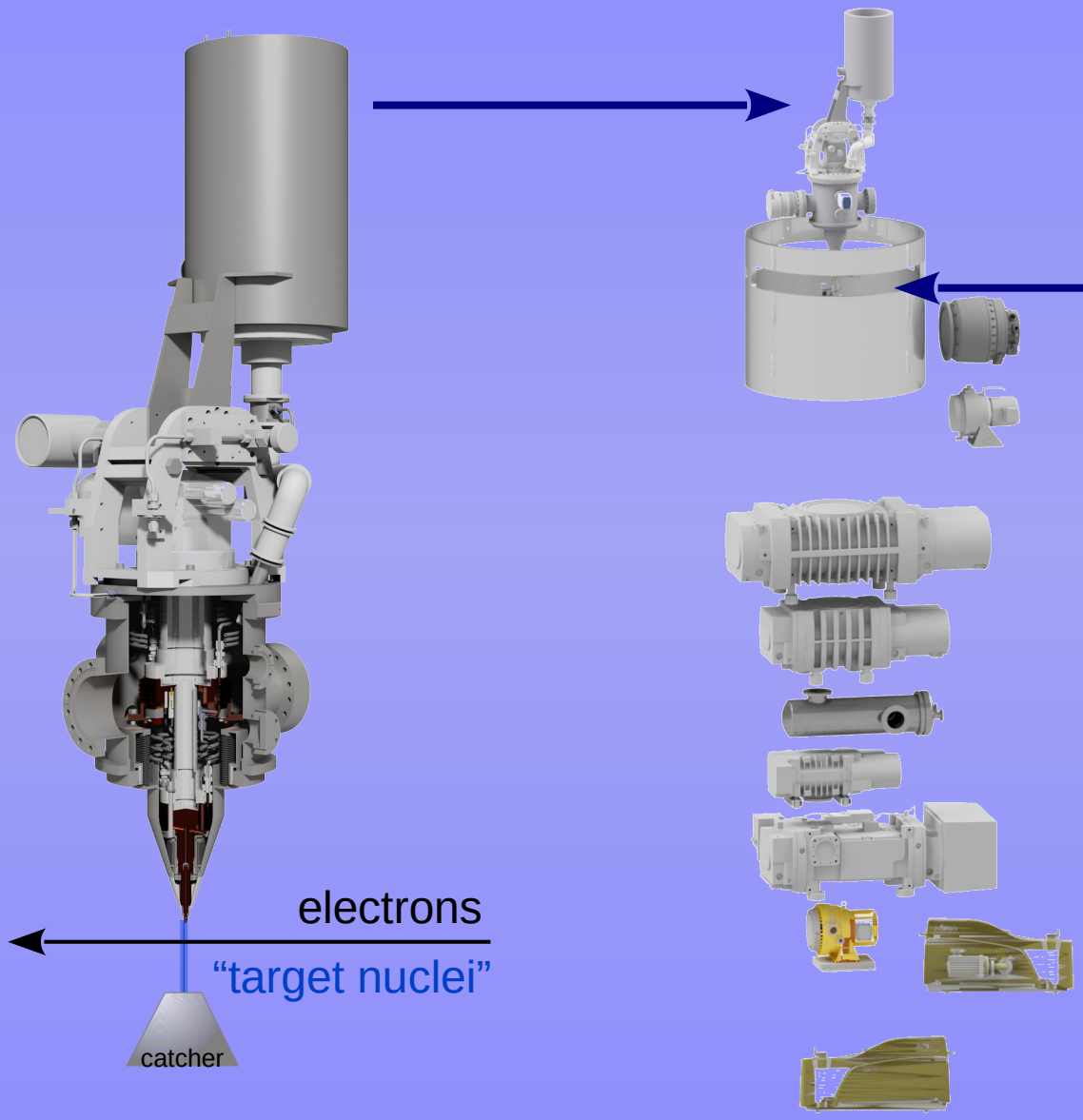

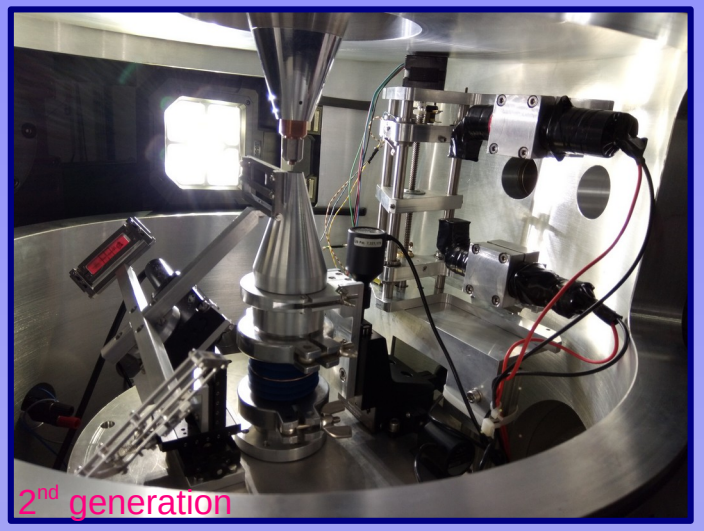

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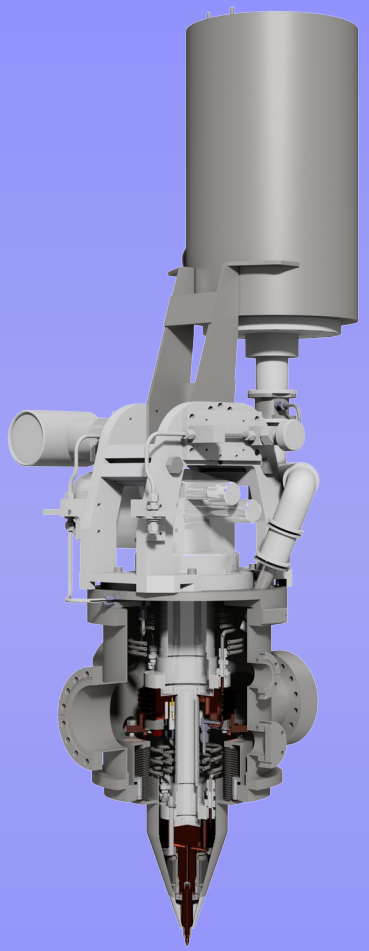
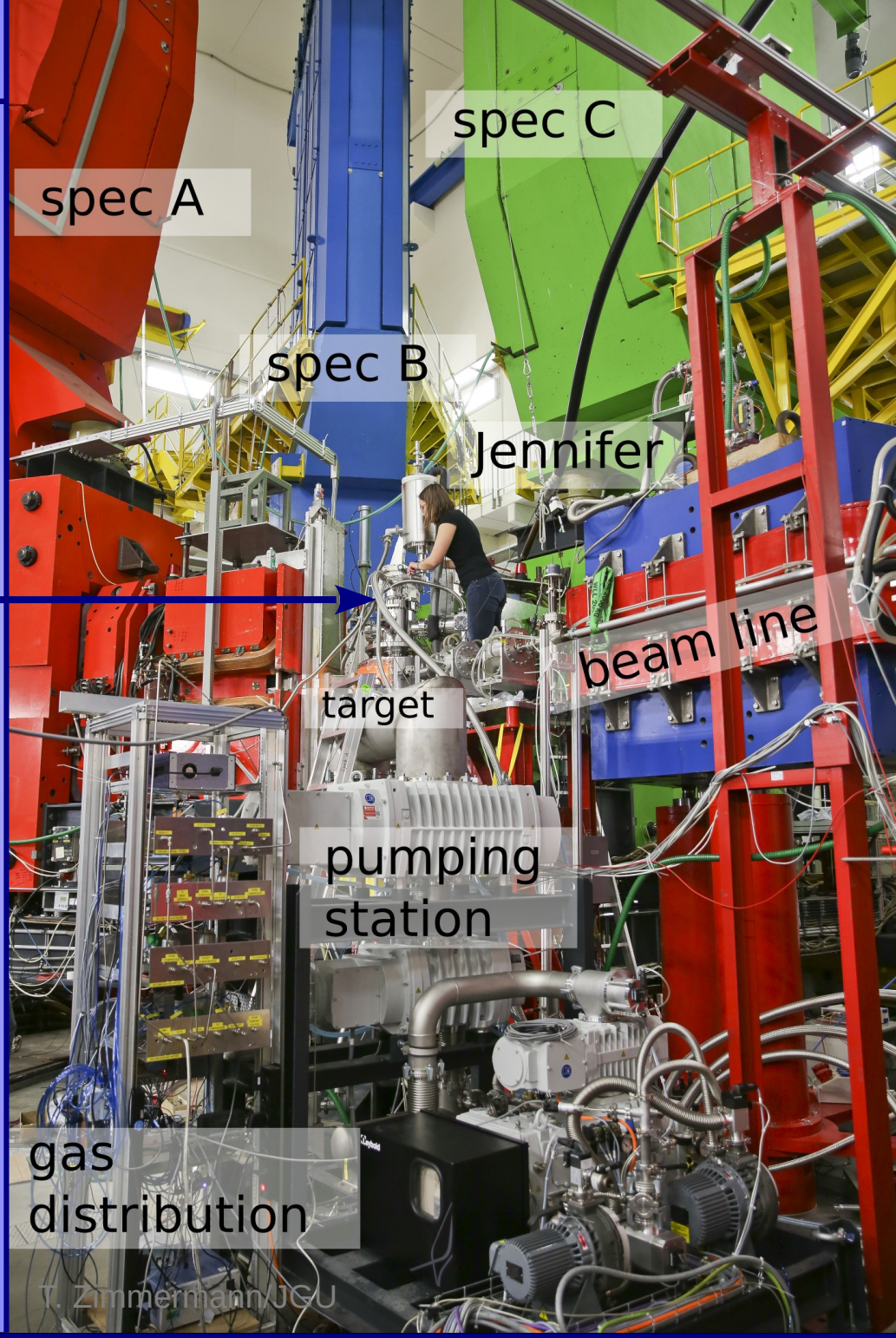


Sept 2017



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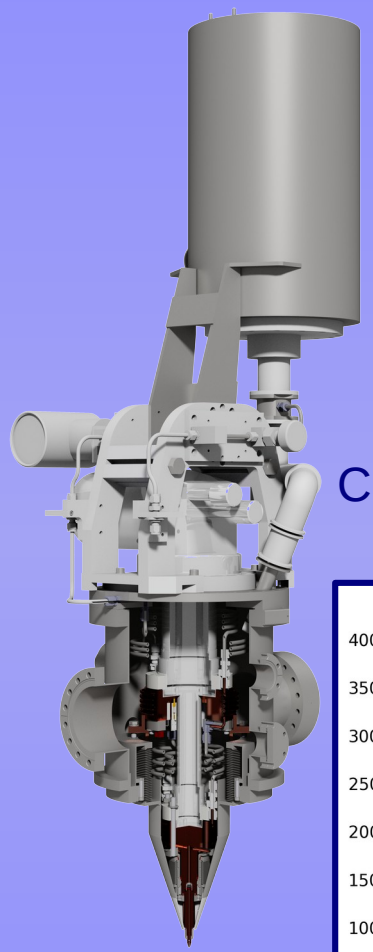
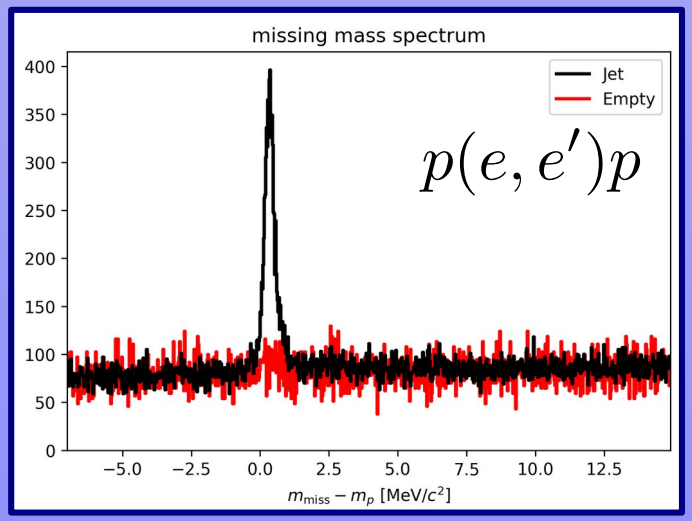
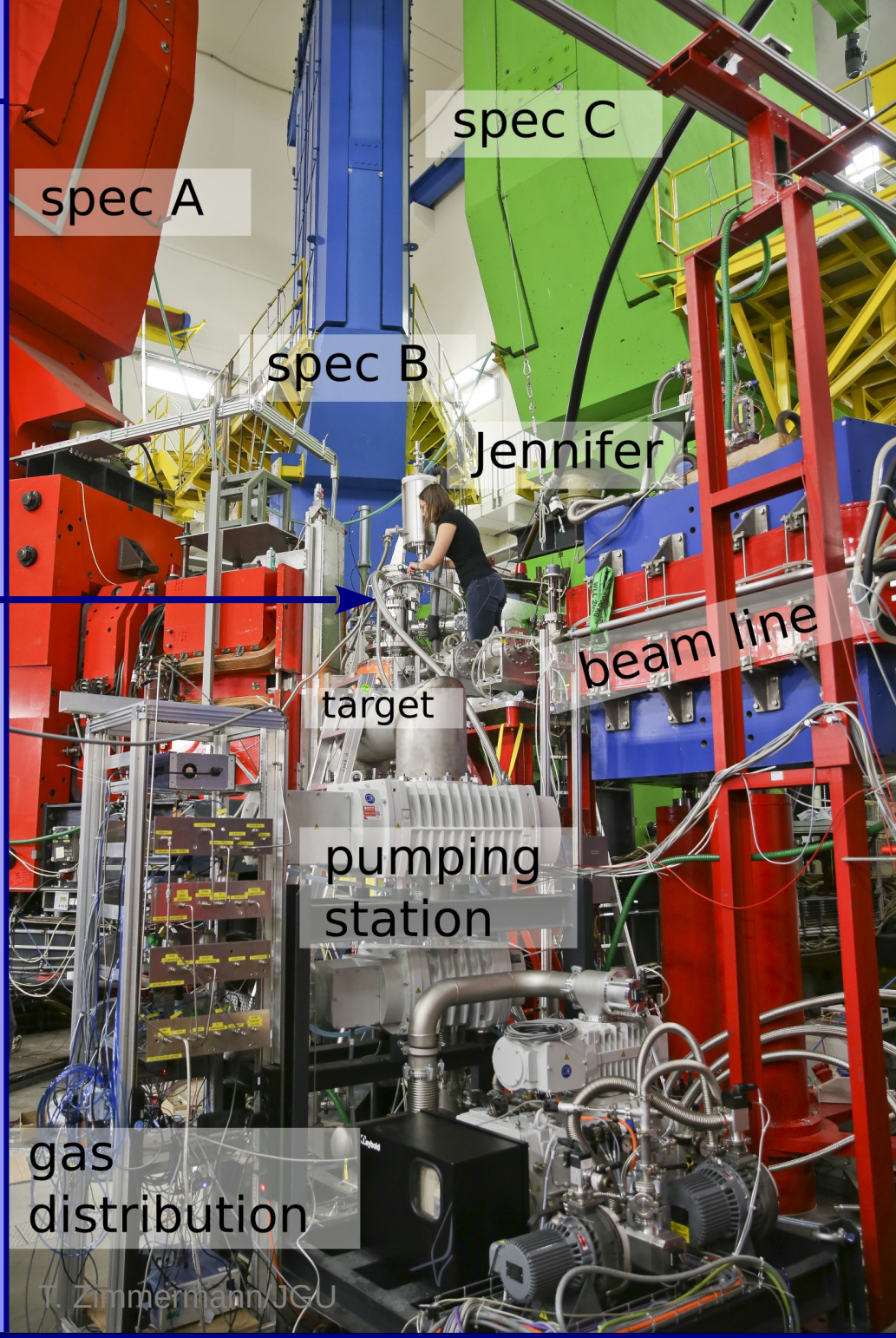


Sept 2017 - Apr 2018

Commissioning, ISR feasibility?



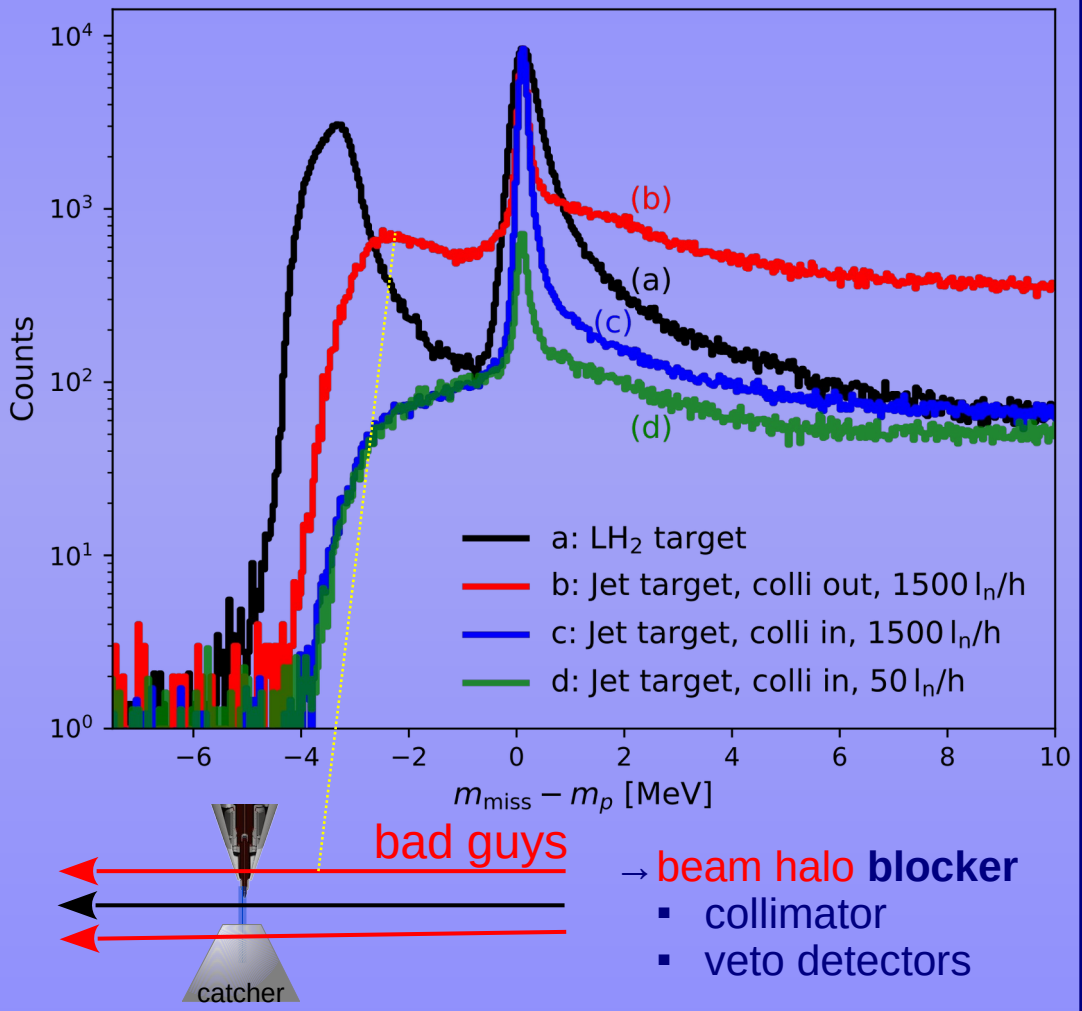
not yet what you would call a background-free experiment



The MAGIX jet target at

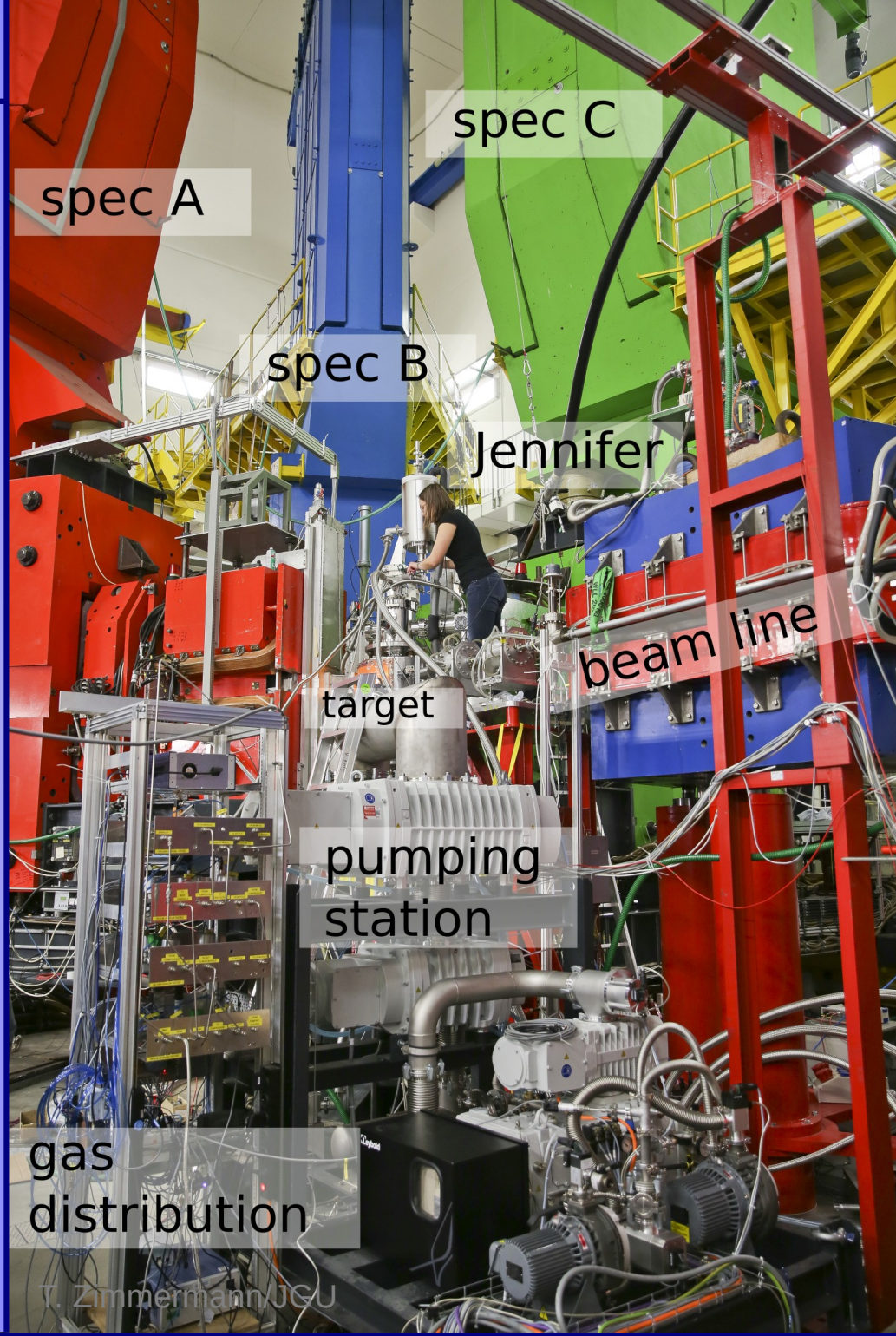
Dec 2019 - Mar 2020

Optimization, proton FF measurements



→ beam halo **blocker**
- collimator
- veto detectors

Operation and characterization of a windowless gas jet target in high-intensity electron beams
B.S. Schlimme *et al.*, NIMA **1013** (2021) 165668



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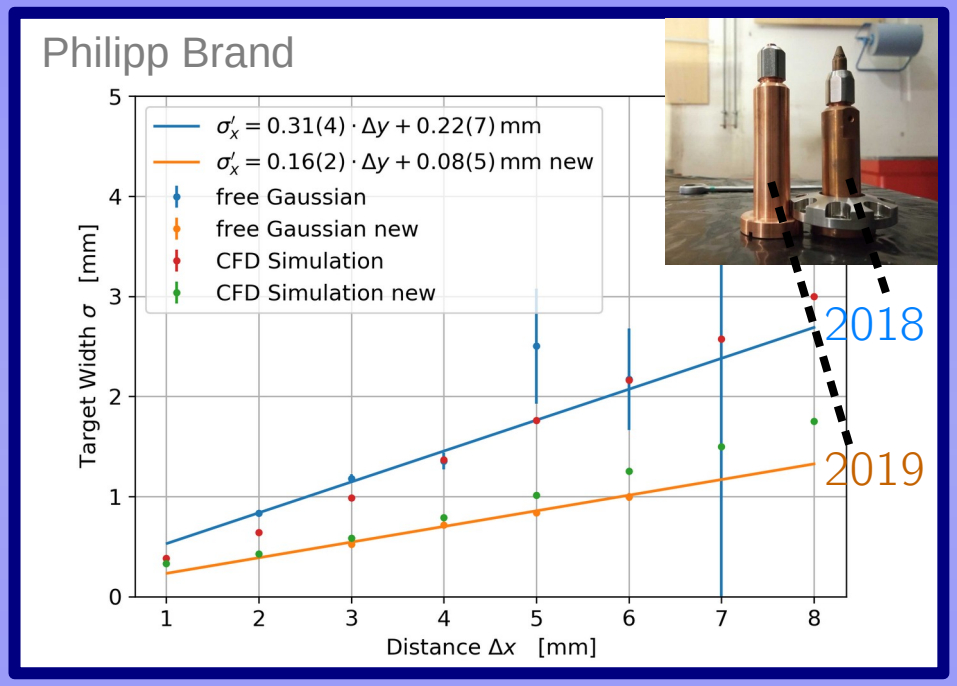

Setup	l [mm]	ρ_{areal} [10^{18} $\frac{\text{atoms}}{\text{cm}^2}$]	I_{beam} [μA]	$\mathcal{L}$ [10^{35} cm^{-2}s^{-1}]	E_{beam} [MeV]	ΔE_{beam} [keV]	Windowless
gas jet, A1	$\sigma \approx 1$	1	20	0.001	195	0.01	✓
LH_2, A1 (cigar)	50	210000	10	131	195	2944	×
PRad	40	2	0.01	0.00001	2200	0.13	(✓)
OLYMPUS	600	0.003	65000	0.01	2000	0.0002	(✓)

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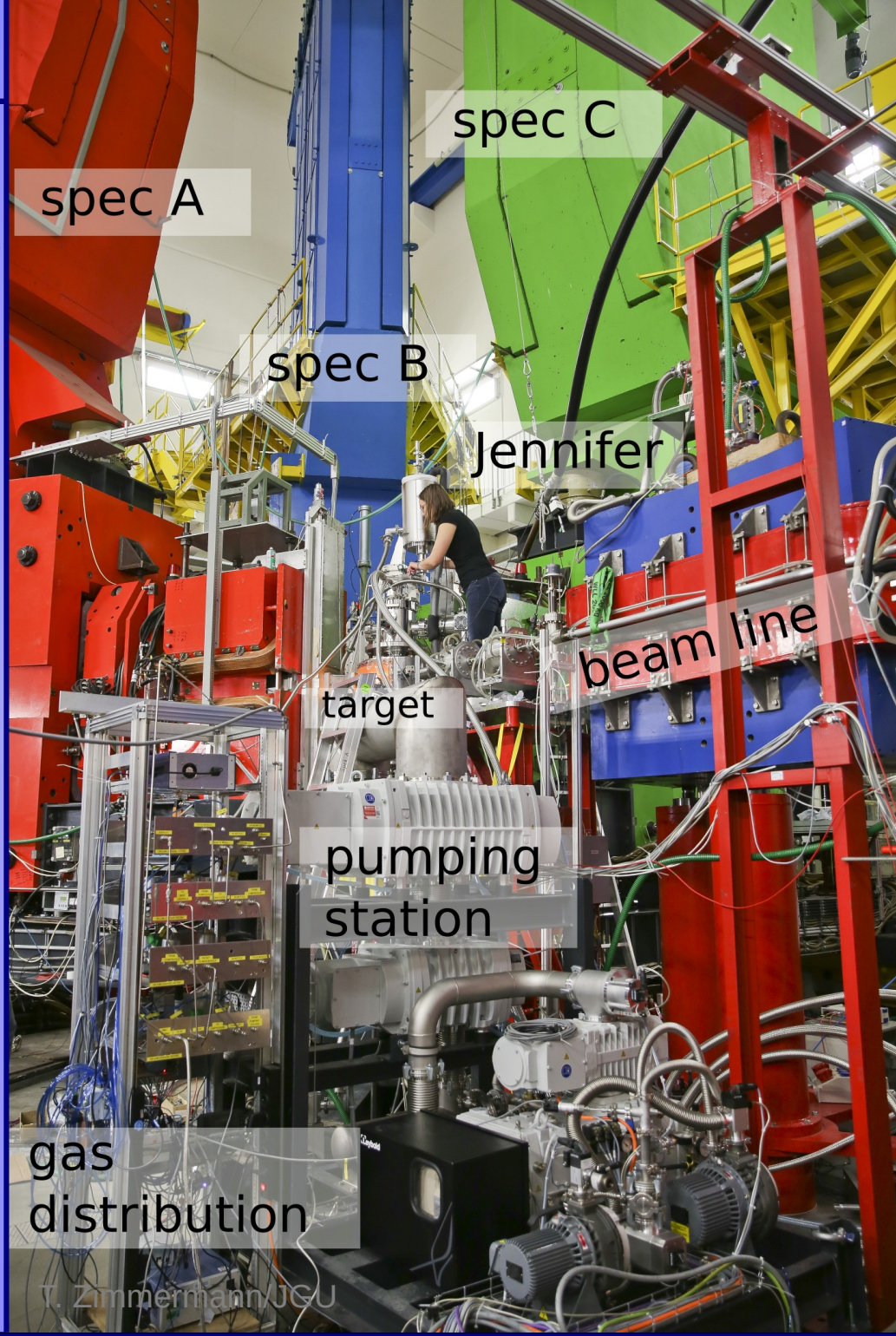

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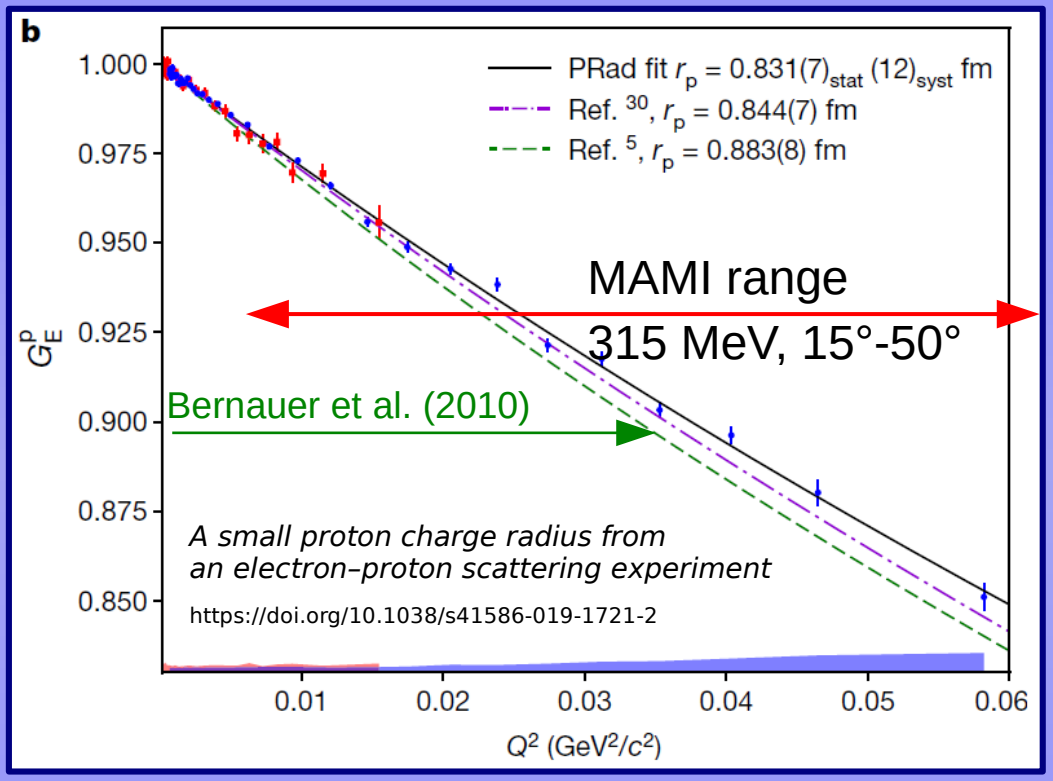

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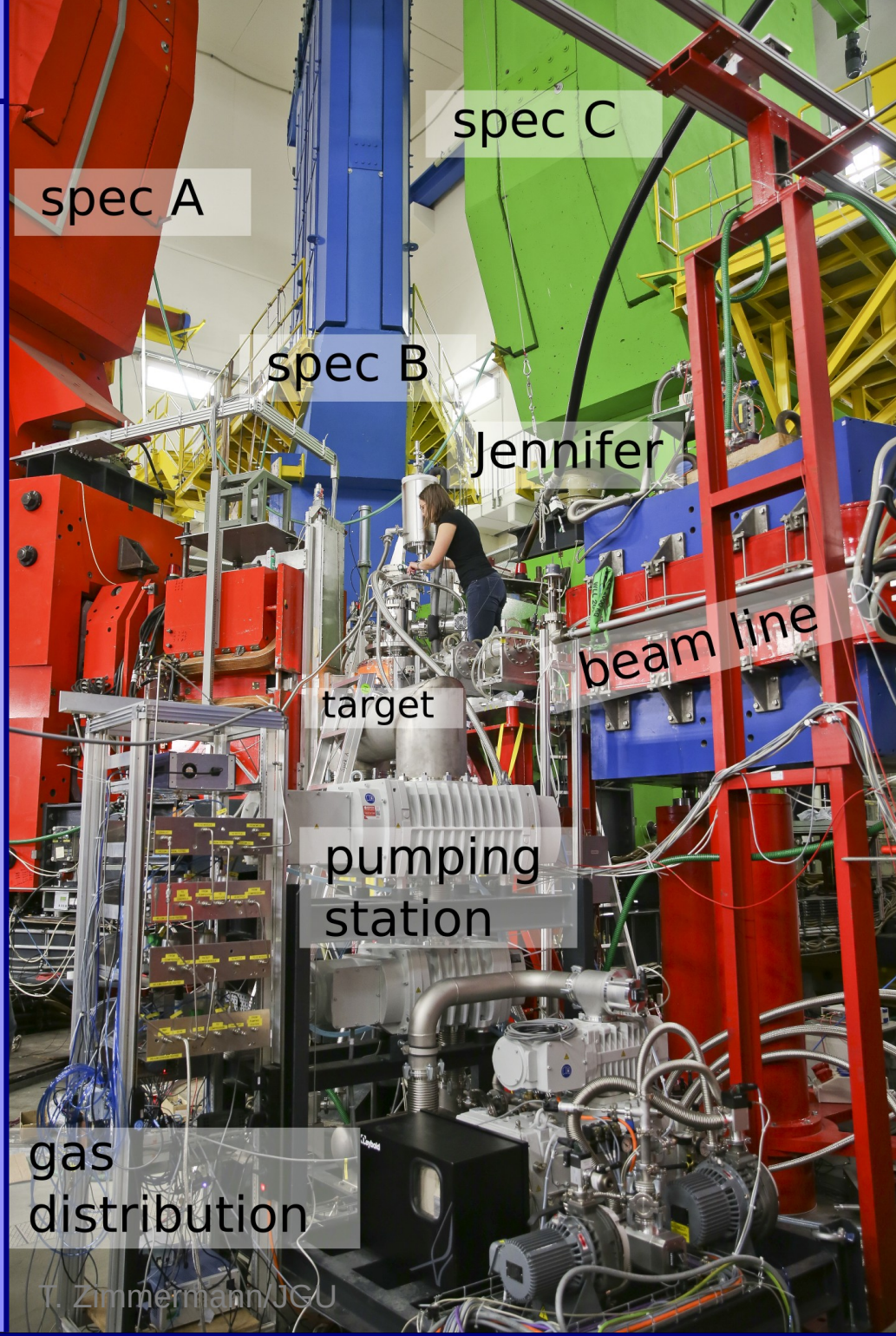
OLYMPUS	600	0.003	65000	0.01	2000	0.0002	(✓)

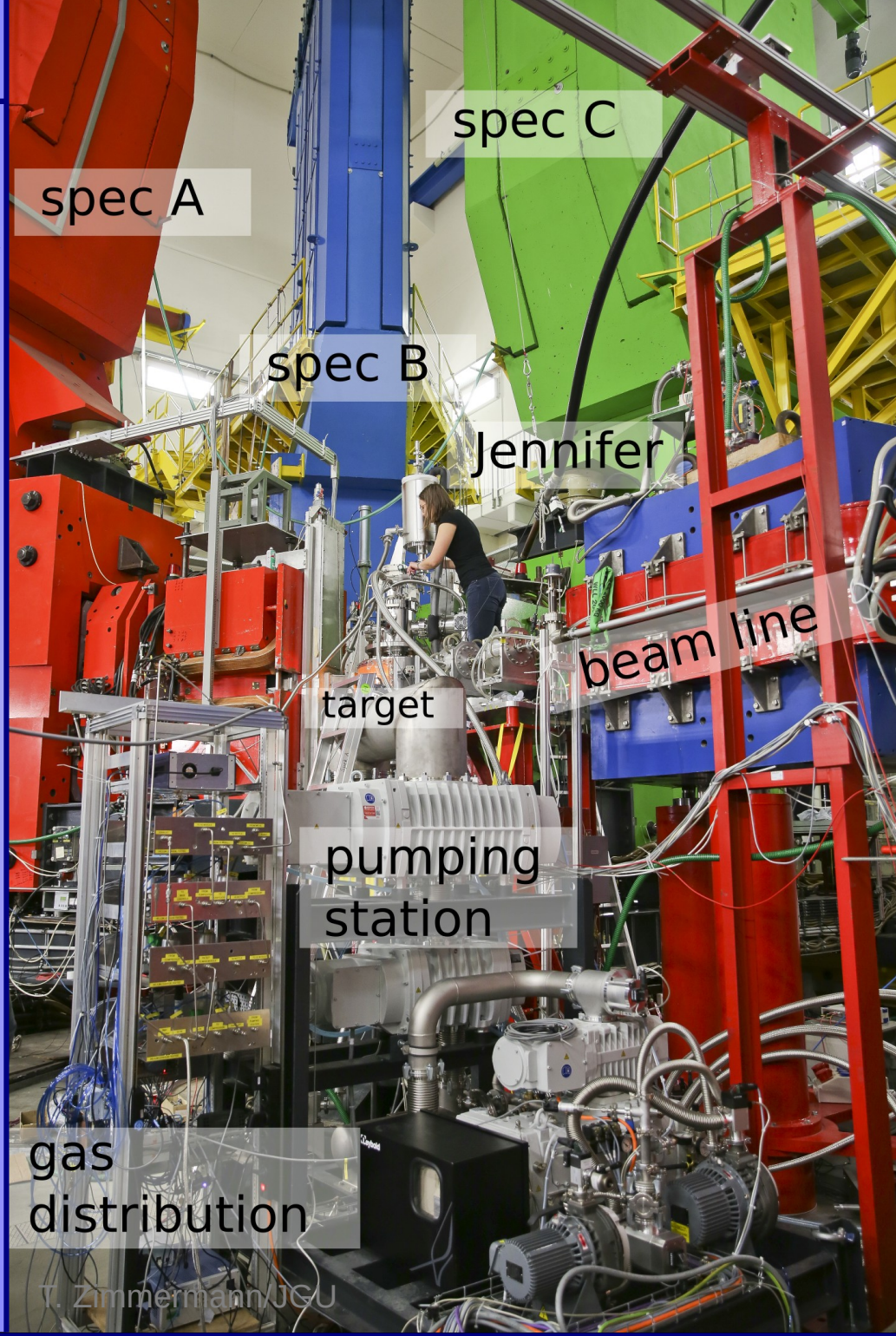
And now: production data.
A1(2010) vs. PRAD.



The MAGIX jet target at

Mar 2020 - Sept 2021

Little break



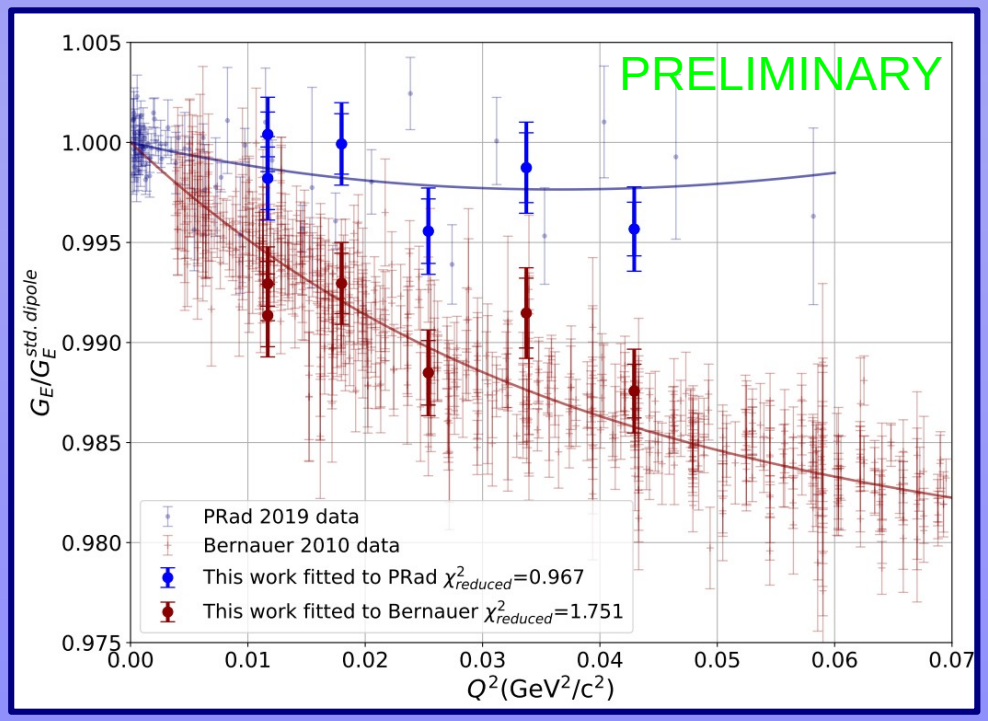
The MAGIX jet target at

Sept 2021 - Nov 2021

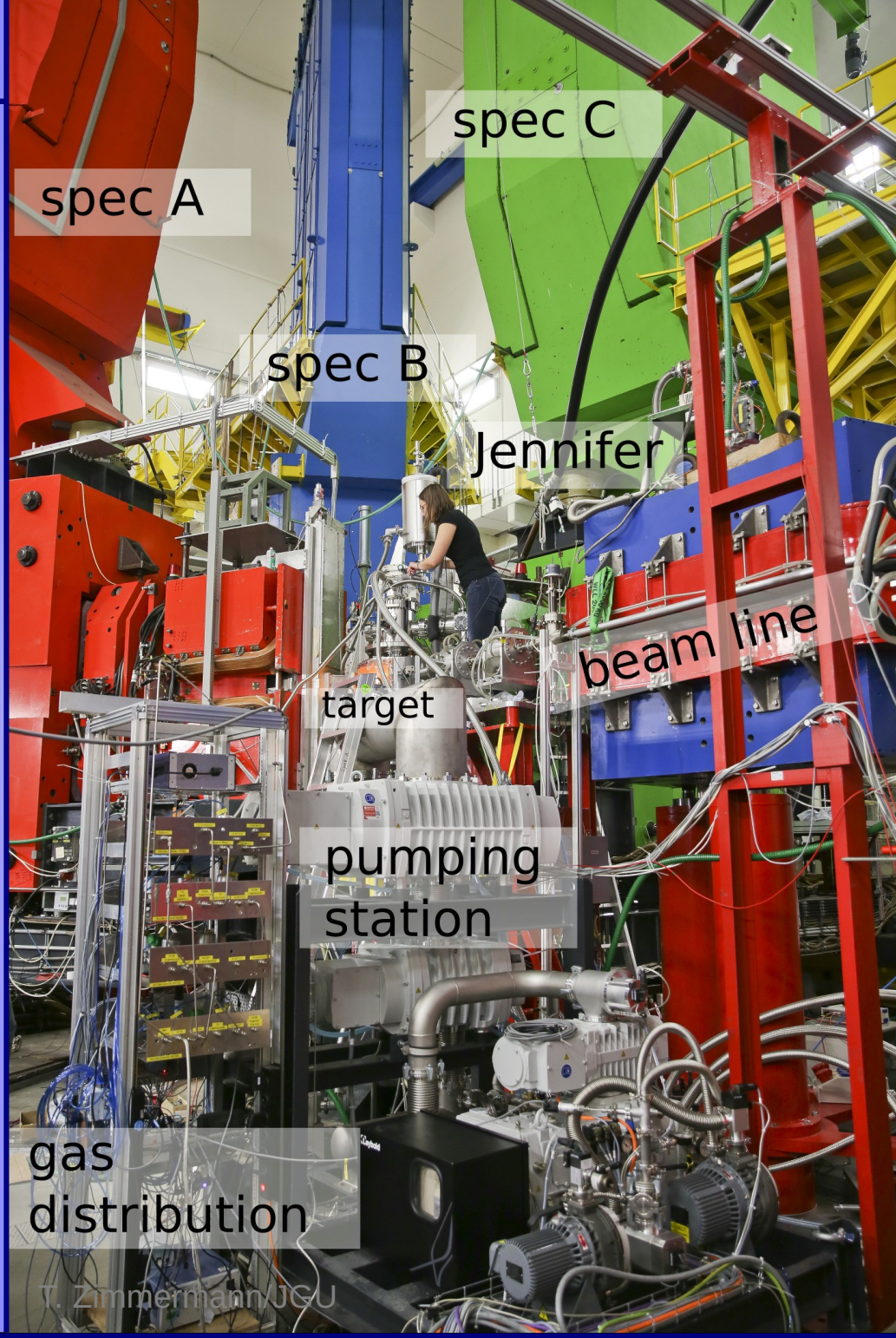
proton FF - final systematic studies;
quasi-elastic scattering on argon (first time)

argon data: work in progress
(Max Littich, Luca Doria, ...)

proton data: to be published
(Yimin Wang, ...)

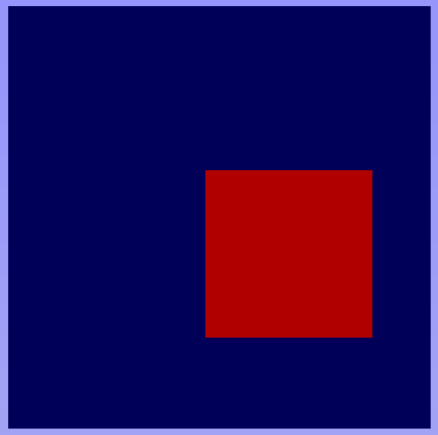


Solid results. However, we were statistically limited.
We need higher beam intensities!



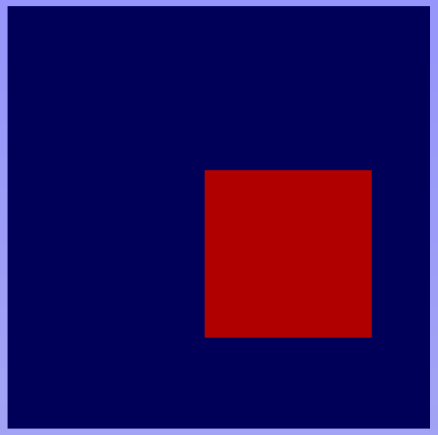
Great plans in Mainz

electron accelerator (MAMI)



scattering experiments (A1)

electron accelerator (MESA)



scattering experiments (MAGIX)

for measurements of the **proton form factors**

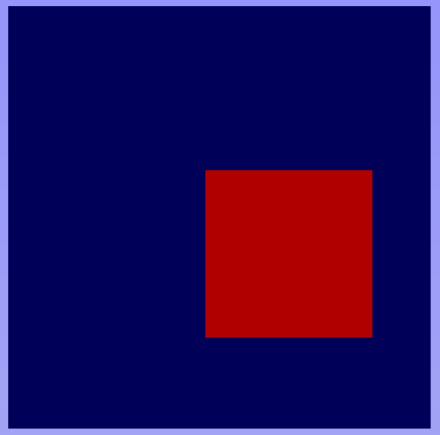
Some people may tell you

- P2 experiment was a main reason for building MESA.
- Original objective of MAGIX was to search for dark photons.

Don't trust them. Run.

Great plans in Mainz

electron accelerator (MAMI)



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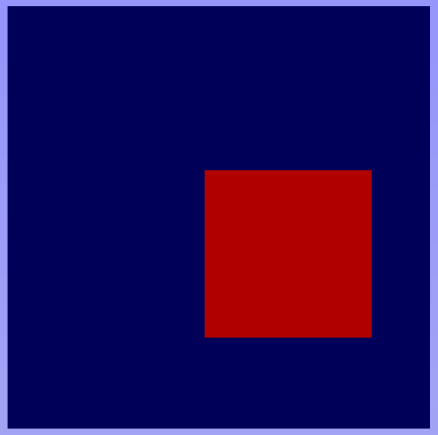

scattering experiments (MAGIX)

for measurements of the proton form factors

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Don't trust them. Run.

world's largest microtron

MAMI

$e, \vec{e}$ 180-1600 MeV 0-100 μA

A1

magnetic spectrometer

energy recovering linac

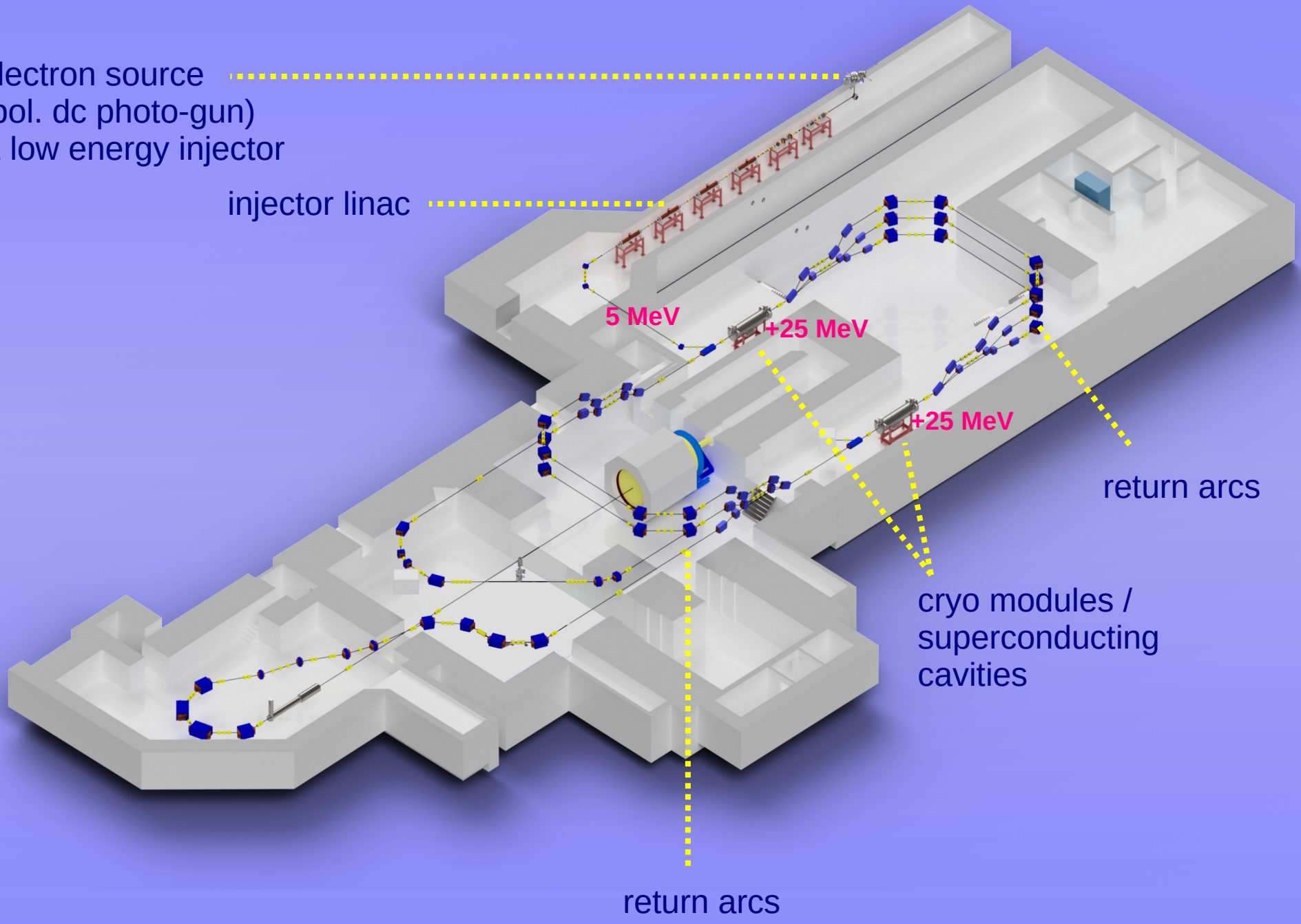
MESA

$e, \vec{e}$ ~20-105 MeV 0-10000 μA

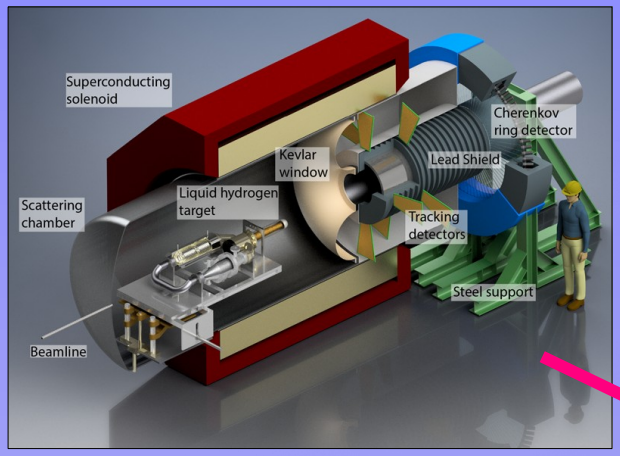
MAGIX

nobody likes the **green** one

MESA: Mainz Energy-Recovering Superconducting Accelerator



MESA EB-mode: P2 & DarkMESA



P2 experiment
Parity violating electron scattering;
main obj.: weak mixing angle

Pb Glass
Veto System
PbF_2

3×
3×
up to 155 MeV

Detection unlikely but possible!

χ

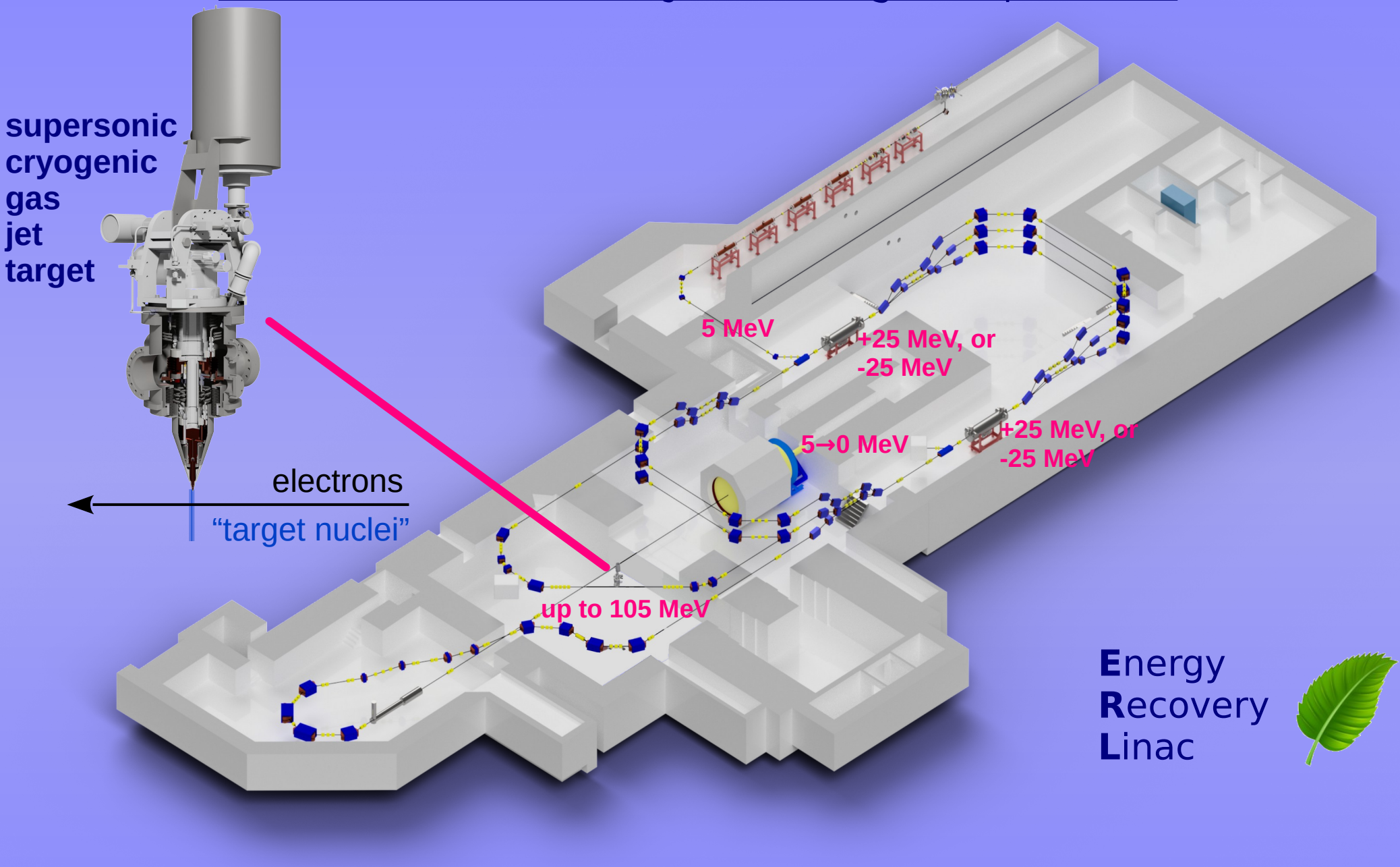
e

dark matter particles may be produced and may pass the dump

big fat beam dump;
no SM particles
shall pass

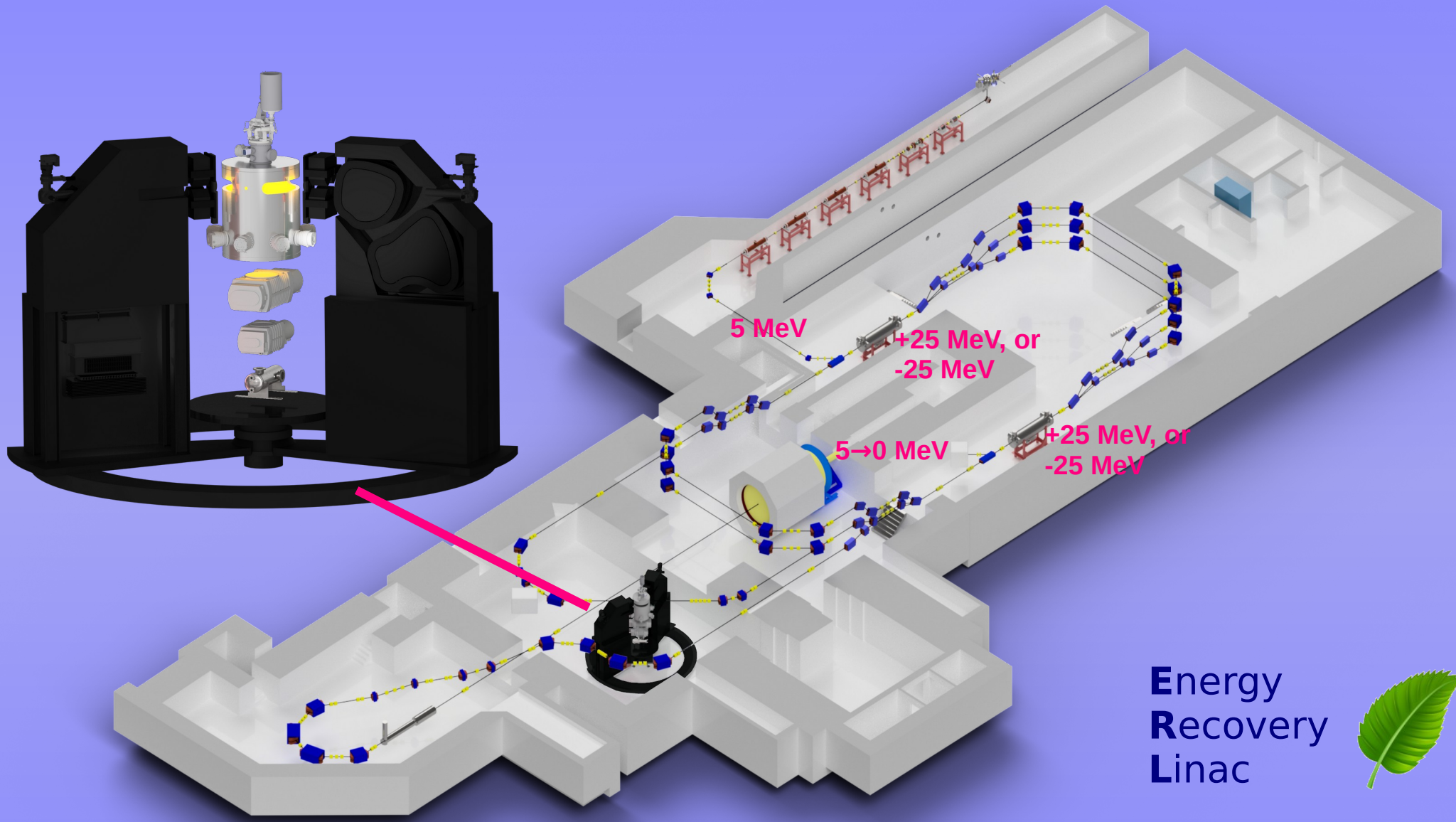
P2/DM-EB mode: polarized electron beam, ~155 MeV, 150 µA

MAGIX: MAinz Gas Injection target eXperiment



P2/DM-EB mode:	polarized electron beam,	~155 MeV,	150 µA
ERL mode:	(un-)polarized electron beam,	20-105 MeV,	10000 µA
MX-EB mode:			150 µA

MAGIX: MAinz Gas Injection target eXperiment

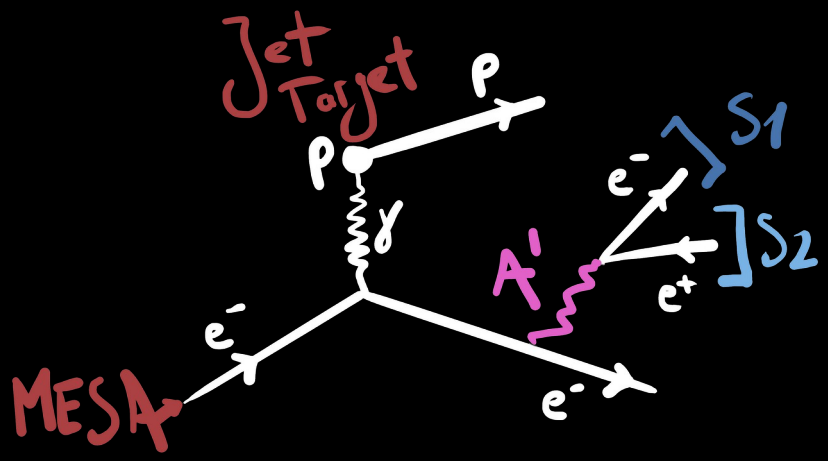


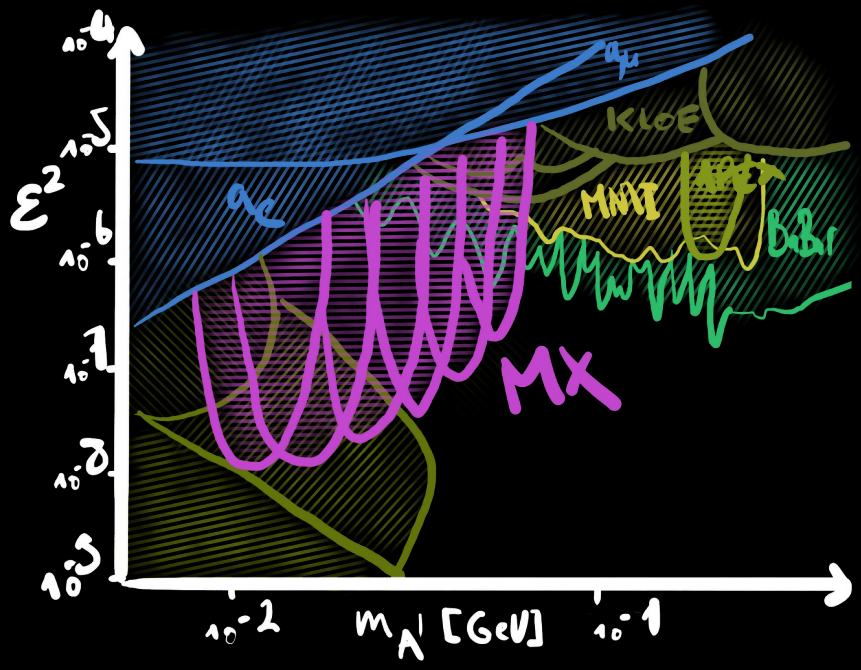
Energy
Recovery
Linac

P2/DM-EB mode:	polarized electron beam,	~155 MeV,	150 µA
ERL mode:	(un-)polarized electron beam,	20-105 MeV,	10000 µA
MX-EB mode:			150 µA

Original objective of MAGIX was to search for dark photons.

artist: van Gülker

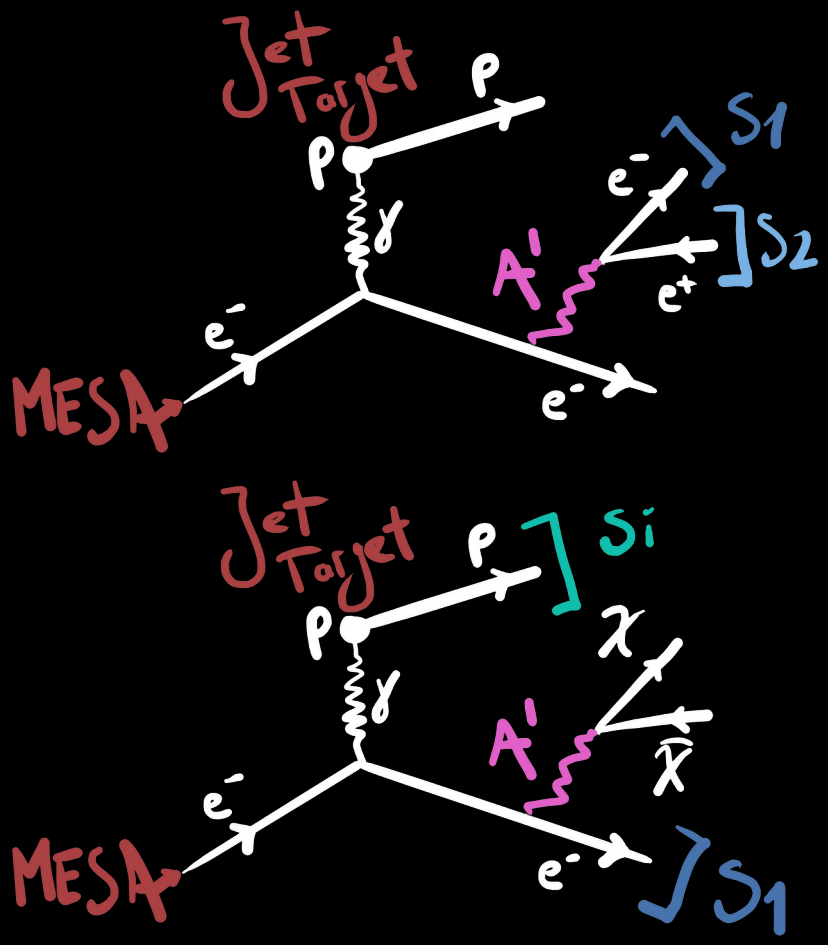


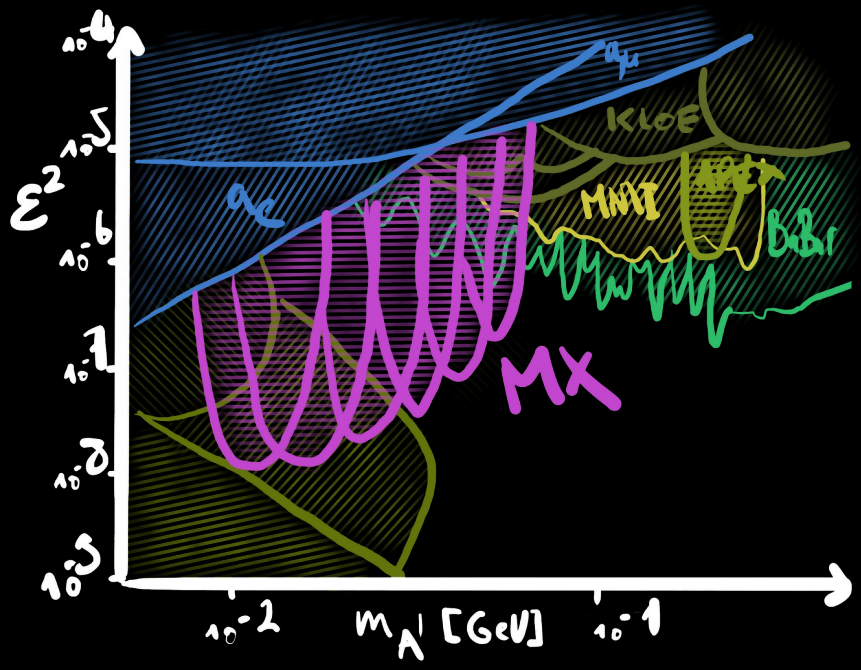


Dark photon search - visible decay

Original objective of MAGIX was to search for dark photons.

artist: van Gülker

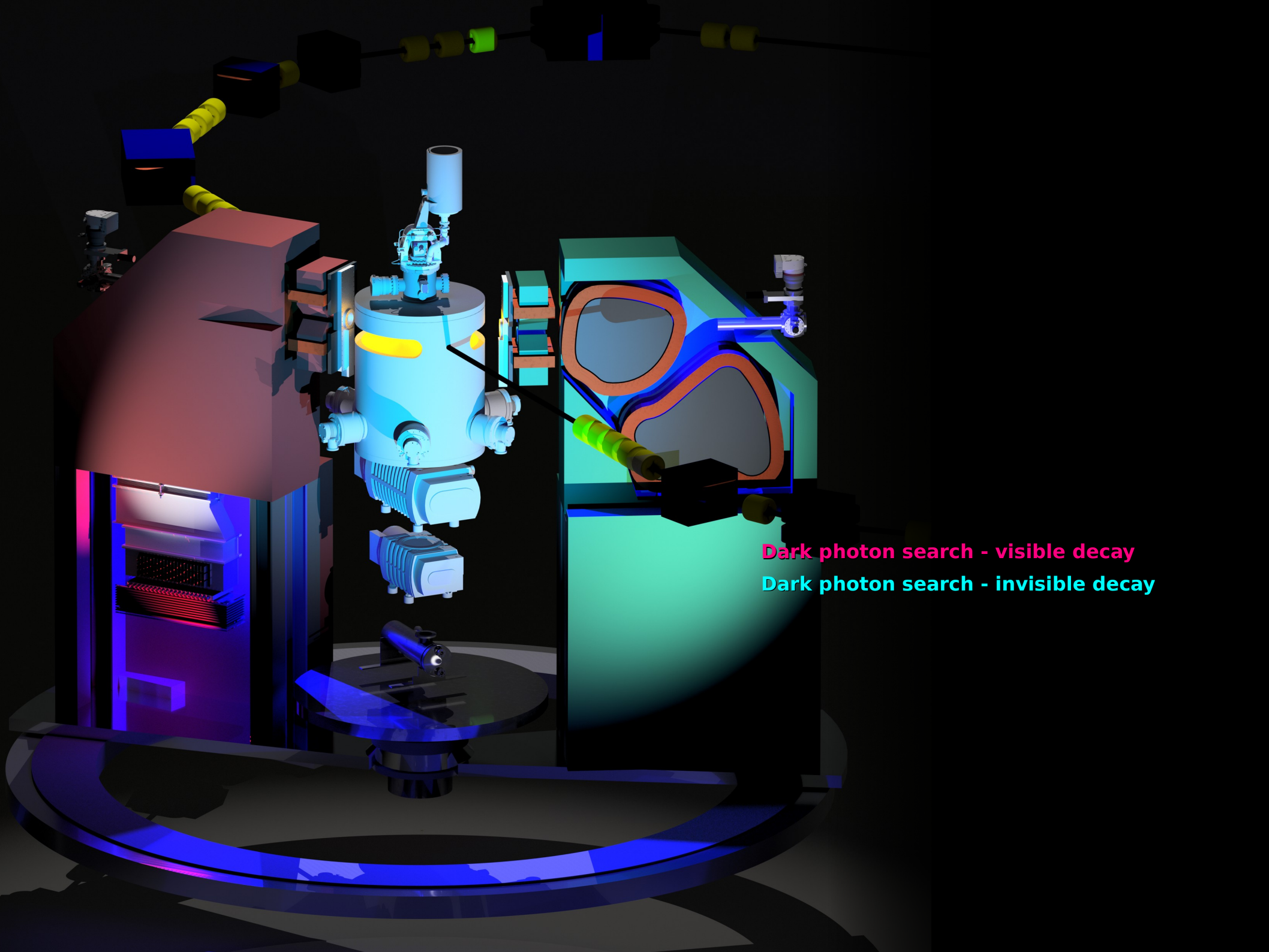


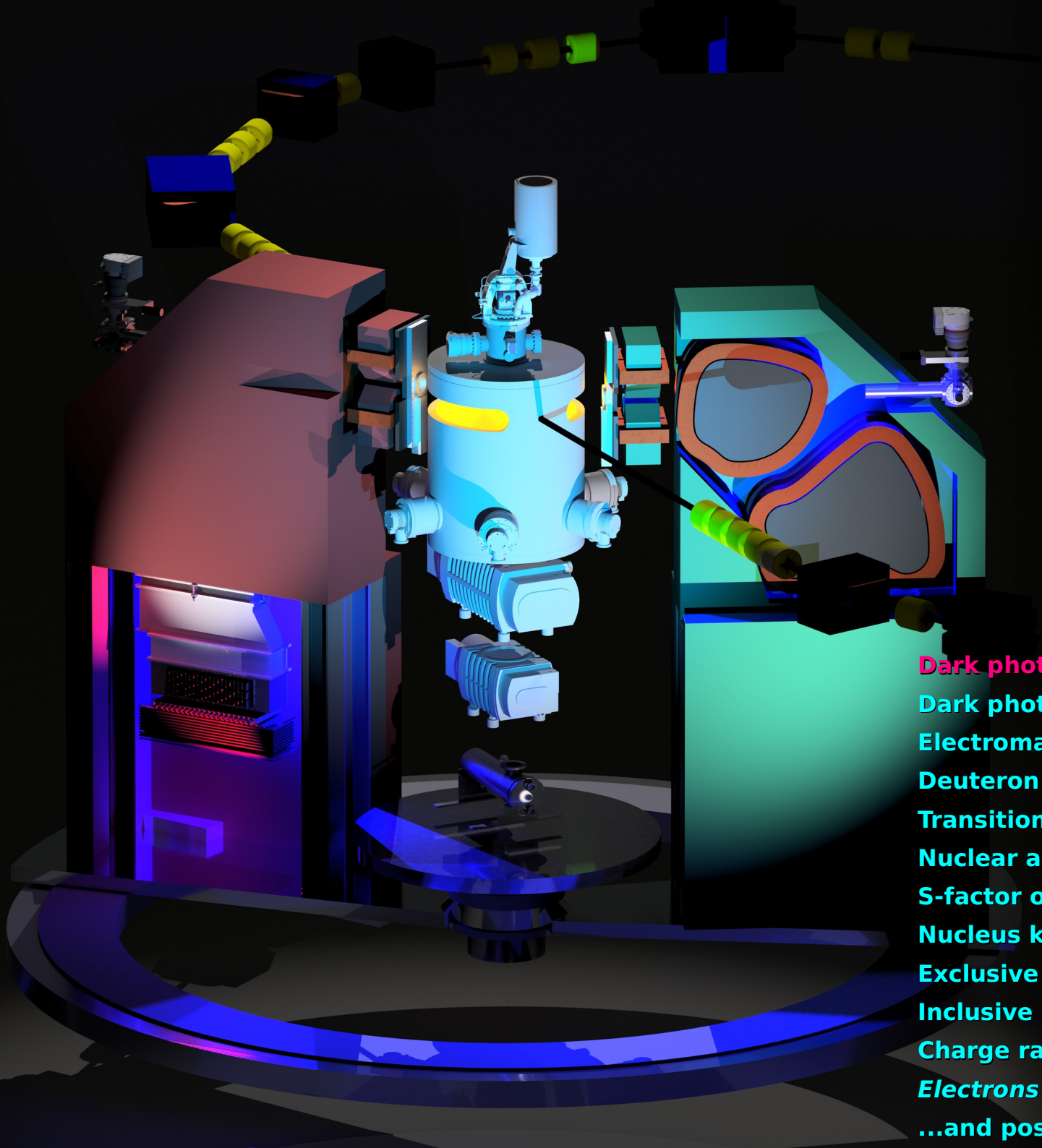


Dark photon search - visible decay

Dark photon search - invisible decay

Original objective of MAGIX was to search for dark photons.


Dark photon search - visible decay
Dark photon search - invisible decay



MAGIX: versatile, high-precision electron scattering experiment

Dark photon search - visible decay

Dark photon search - invisible decay

Electromagnetic form factors of the proton

Deuteron electrodisintegration

Transition form factor of the Hoyle state in ^{12}C

Nuclear astrophysics: (γ,n) reactions

S-factor of the ^{12}C(α,γ)^{16}O - reaction

Nucleus knockout reactions from light nuclei

Exclusive measurements on ^{3}He/^{4}He

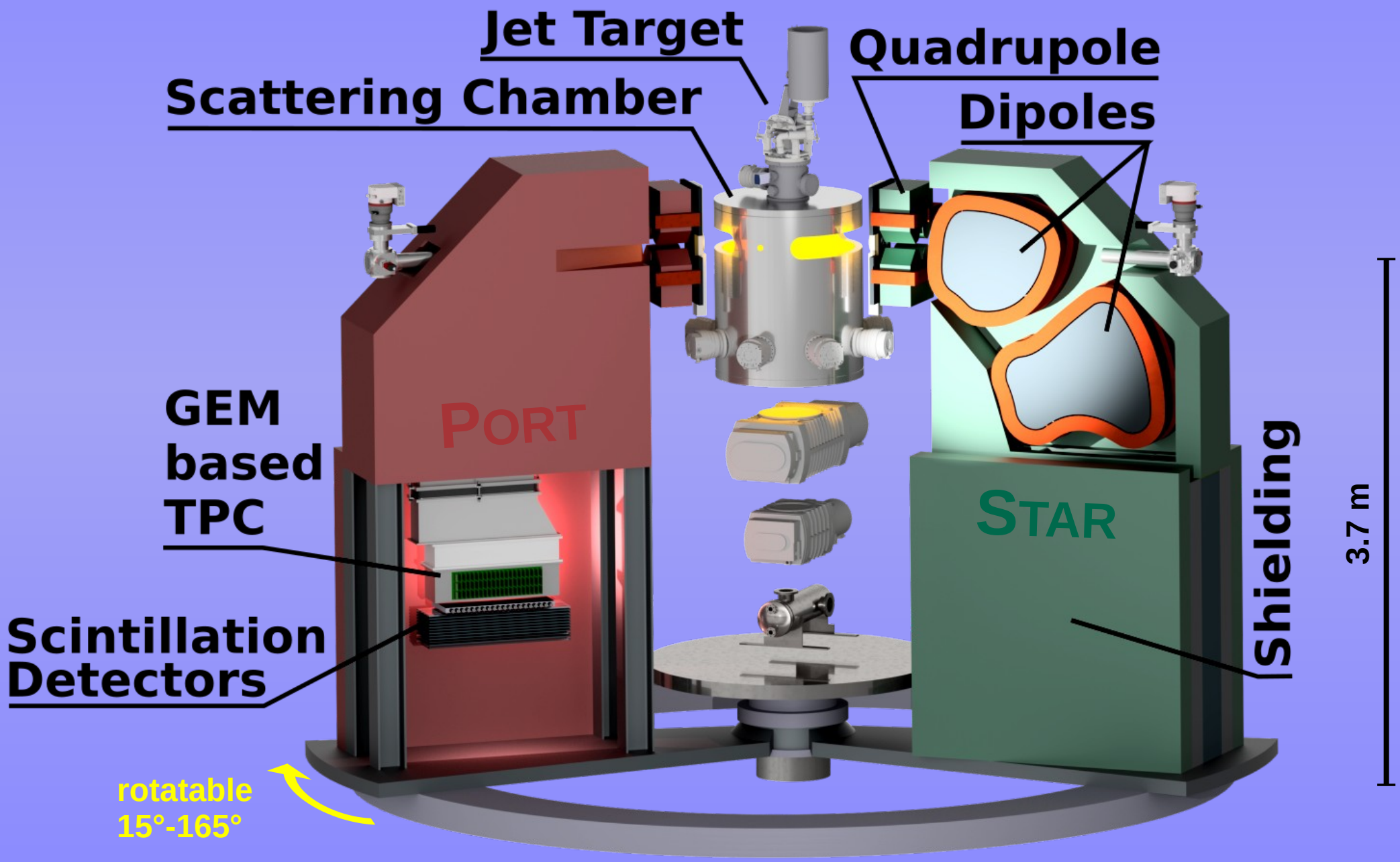
Inclusive measurements on ^{4}He, ^{16}O

Charge radius deuteron, ^{4}He

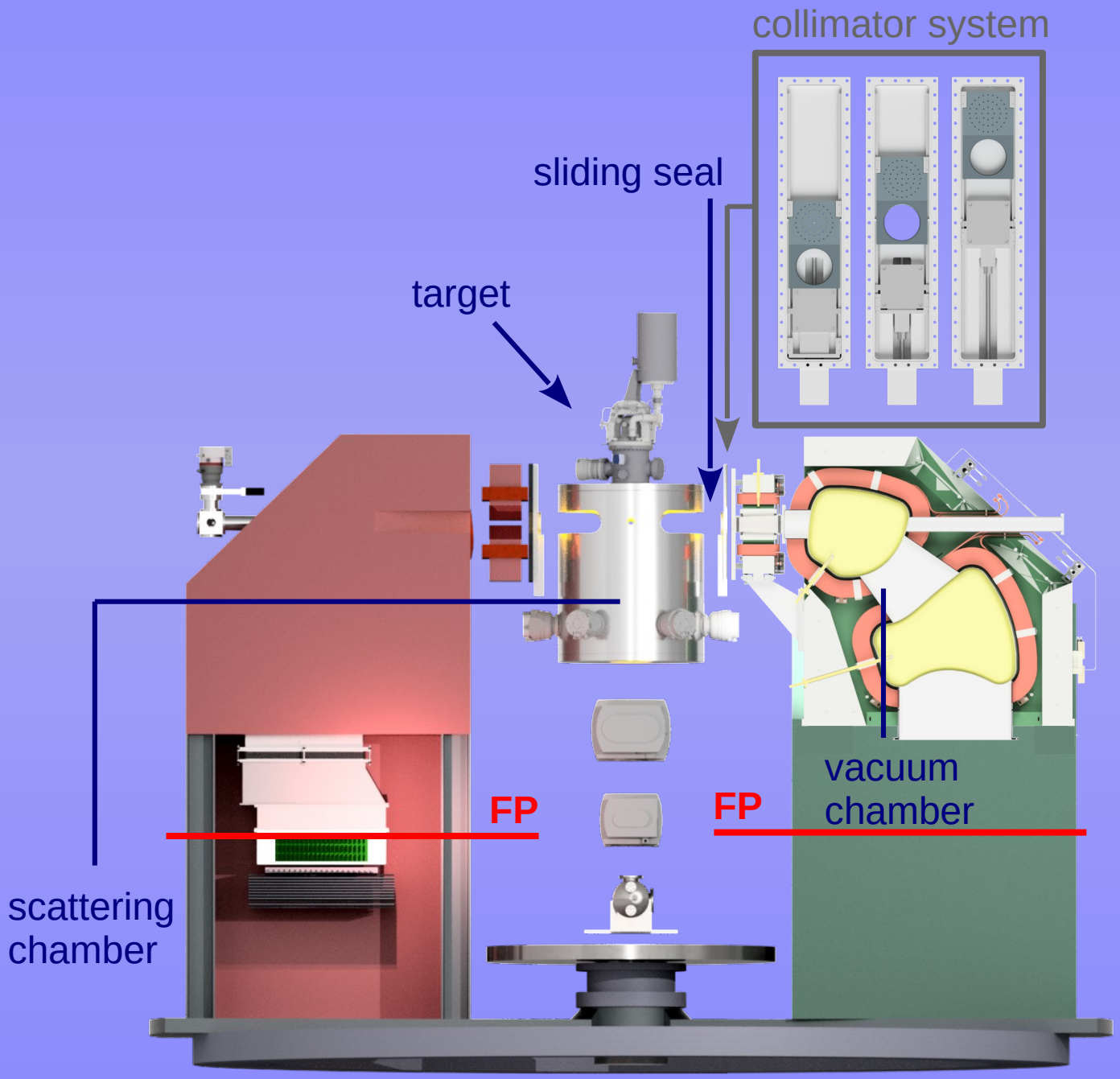
***Electrons for neutrino physics* program**

...and possibly more

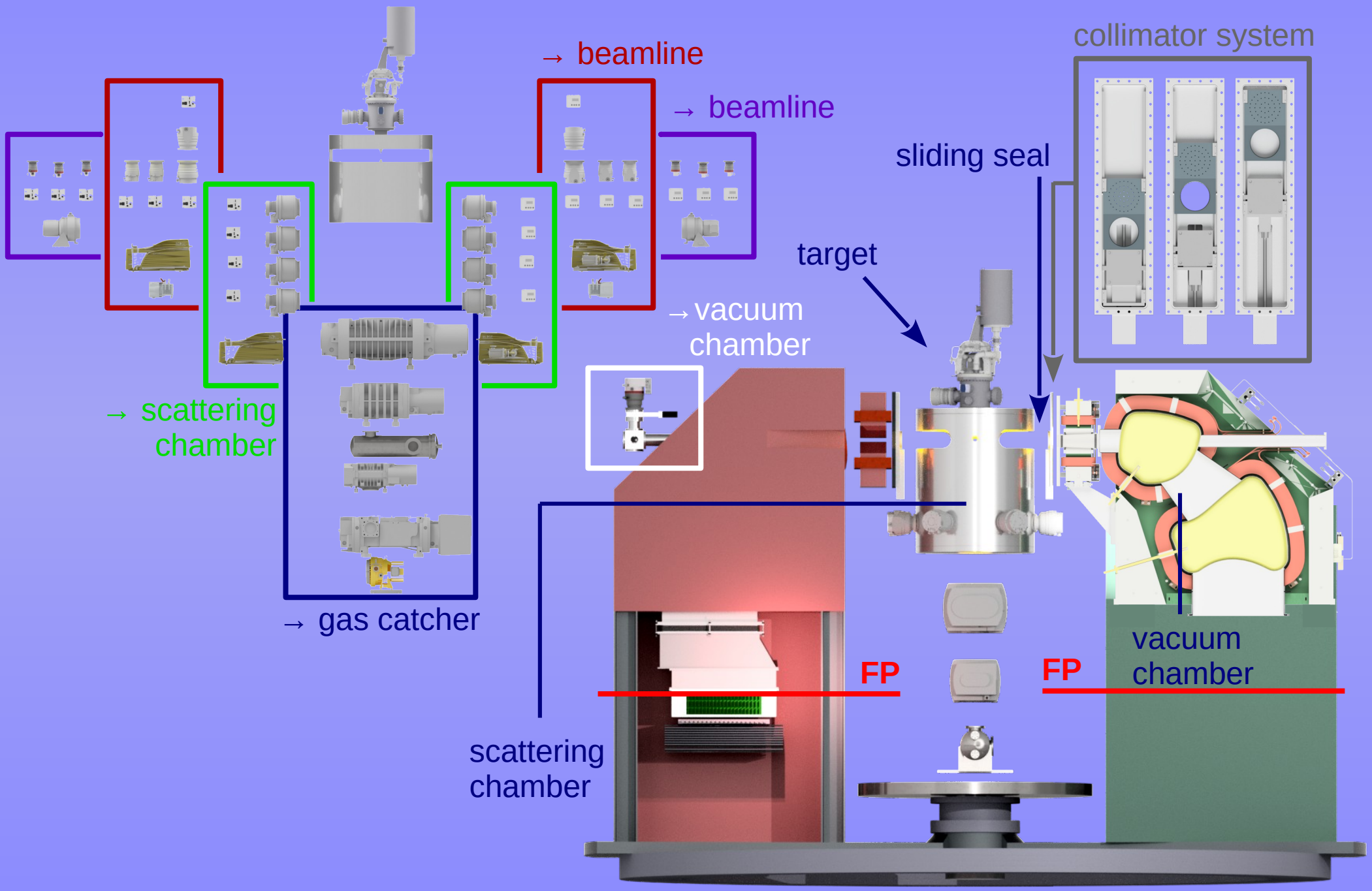
StarPort Spectrometer Setup



Target and Vacuum System



Target and Vacuum System

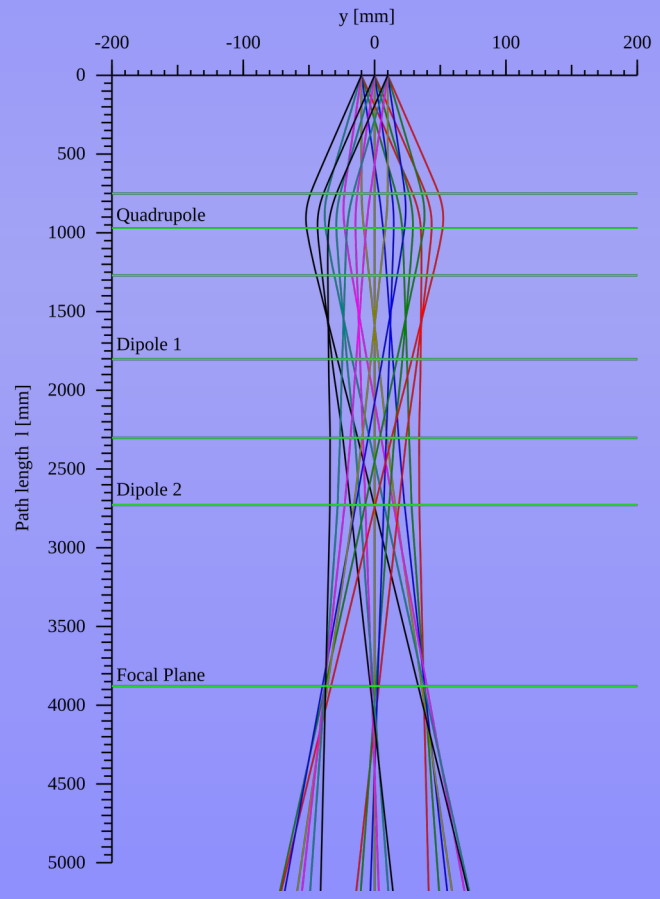


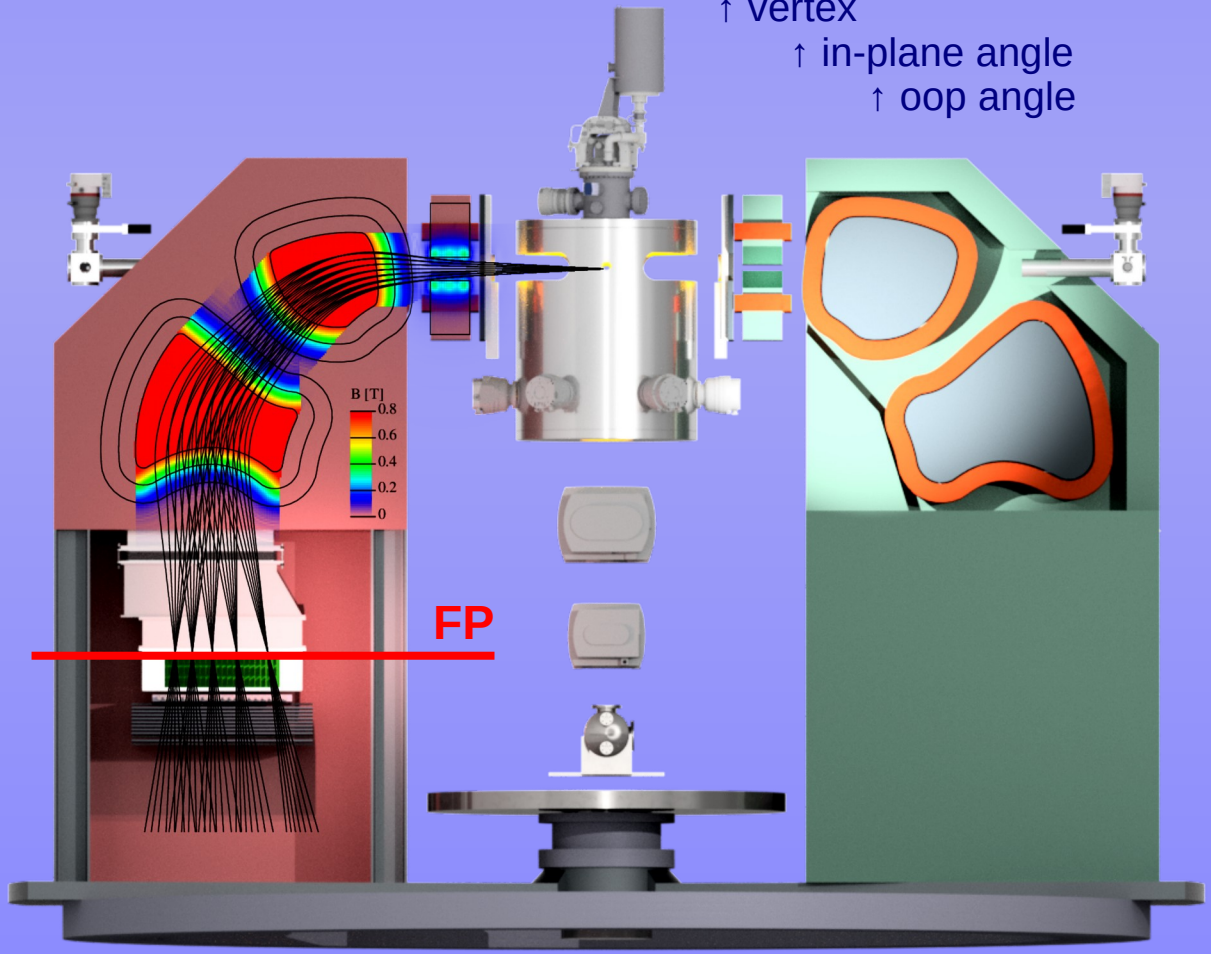
Magnet system, optics

- **quadrupole** followed by two 45° **dipoles**
- special design of pole pieces
  → double-focusing with a horizontal **focal plane (FP)**

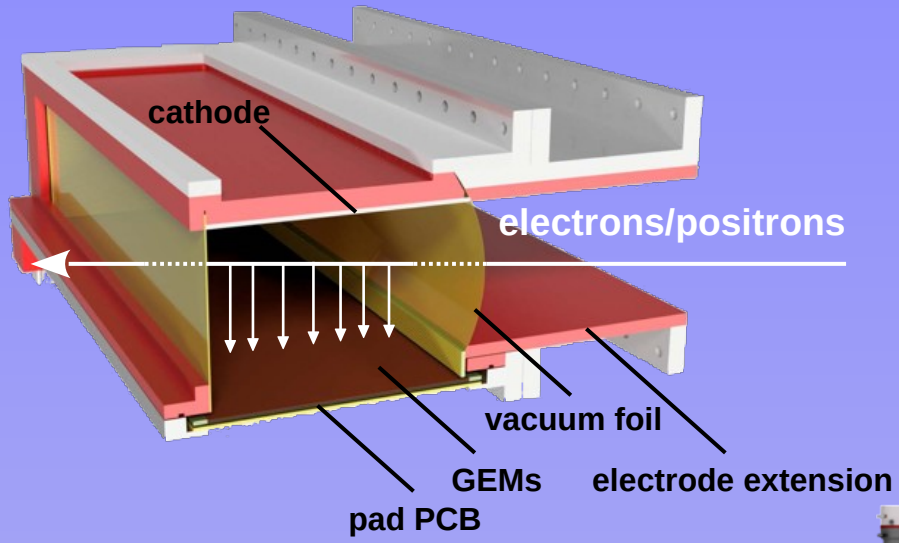
measurement of
focal plane coordinates
(x, y, x', y')
+ knowledge of opt. properties
⇒ **coordinates at target**
$(p, y_0, \phi_0, \theta_0)$

↑ momentum
↑ vertex
↑ in-plane angle
↑ oop angle





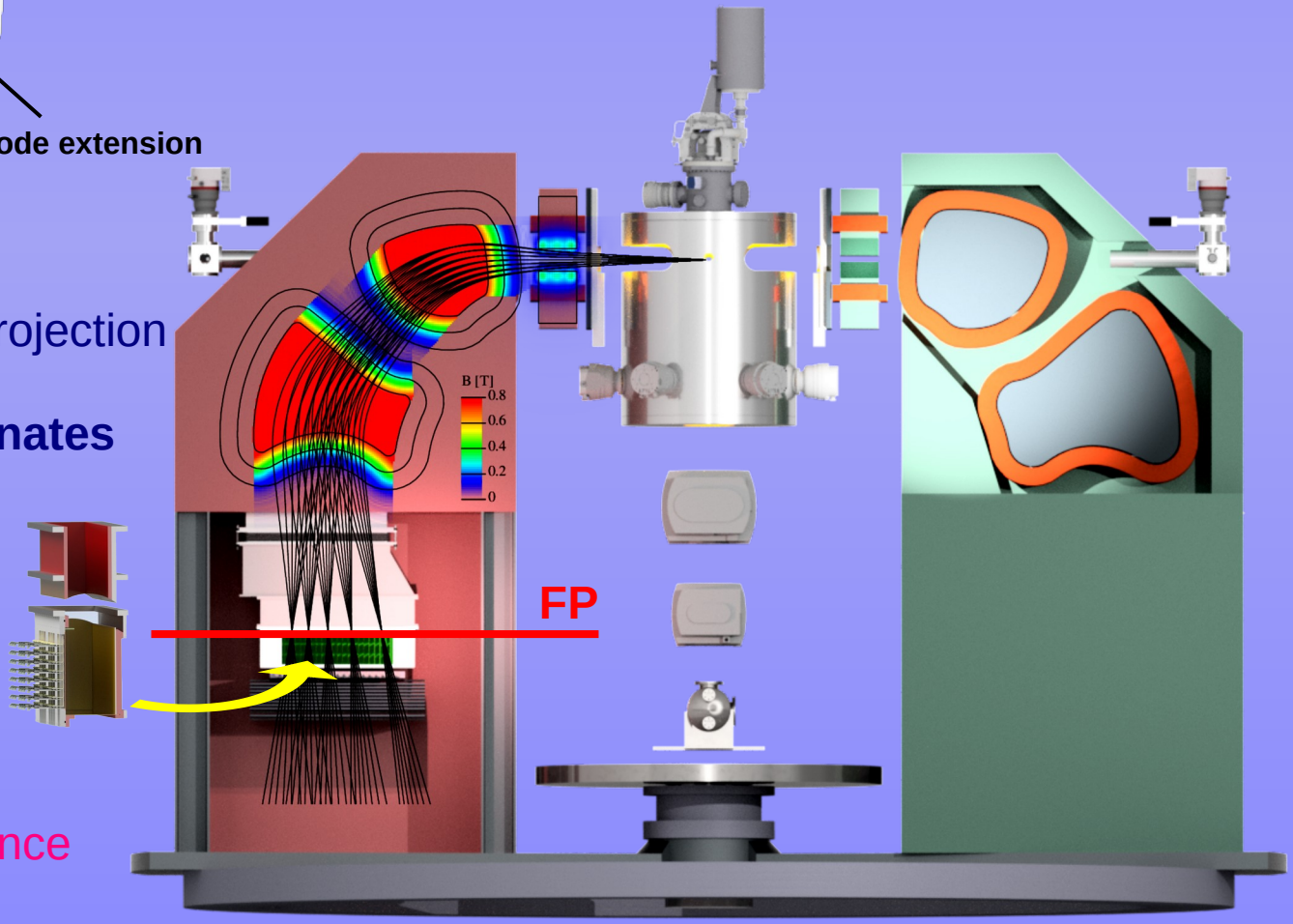
Tracking Detector: MXTPC



GEM-based Time Projection Chamber

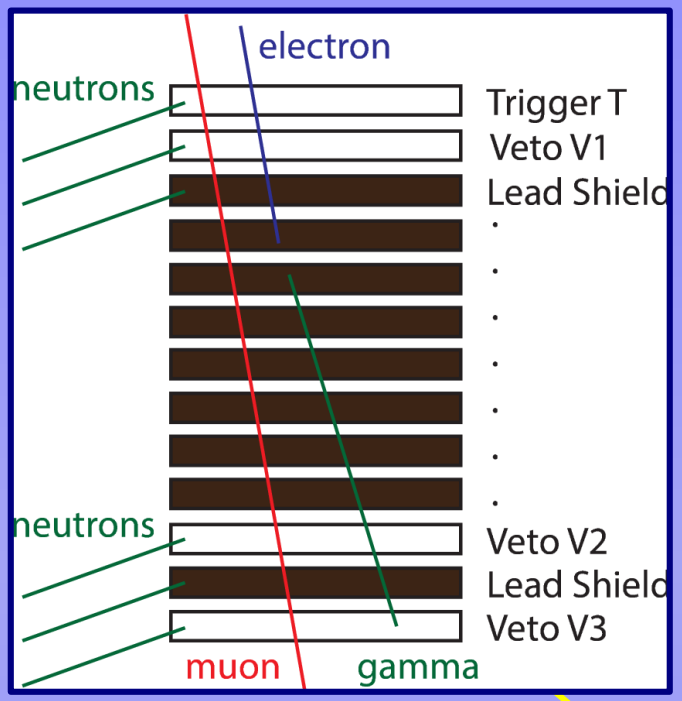
- **electron-ion pairs** along track
- **drift** of secondary electrons in E-field
- quad-GEM **amplification**
- **pad readout,** 24 × 384 = **9216 channels**

- pad hit pattern → 2D track projection
- measured drift time → **3D track**
  → **FP coordinates**
- limiting factor:
  multiple scattering in material
  ↔ minimal material budget



fast, external time-reference detector required below!

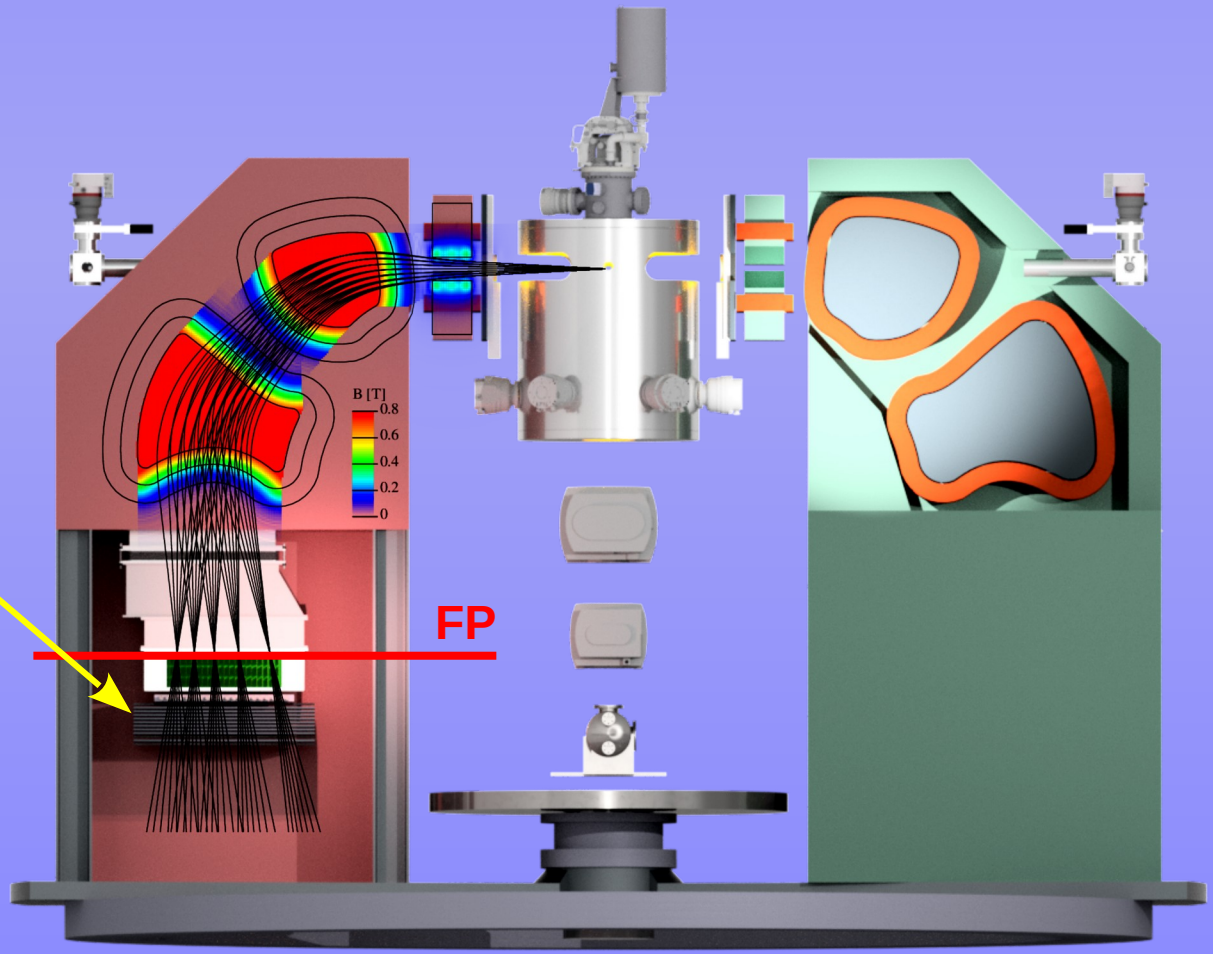
Trigger and Veto System



Trigger / Veto detectors:

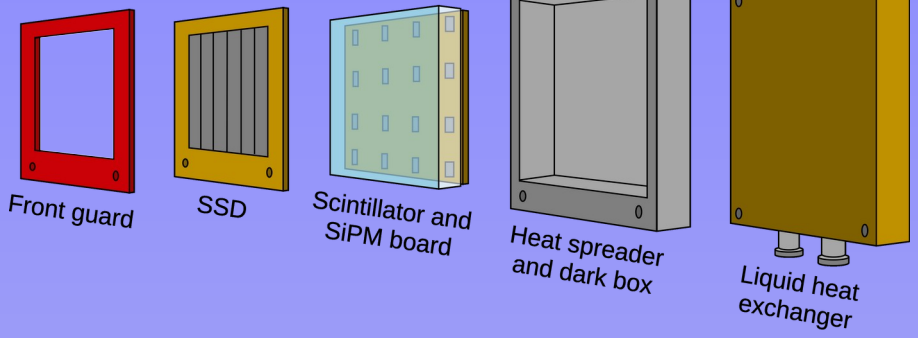
Segmented layers of plastic scintillation detectors;
PMTs, SiPMs;
Lead absorbers / PbGl shower detector (?)

- TPC timing
- data acquisition trigger
- coincidence time
  STAR ↔ PORT
- Particle ID

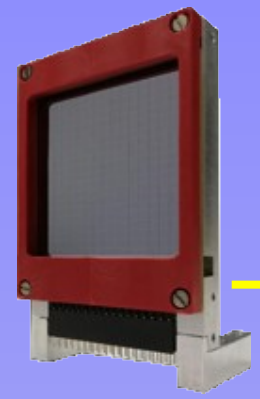


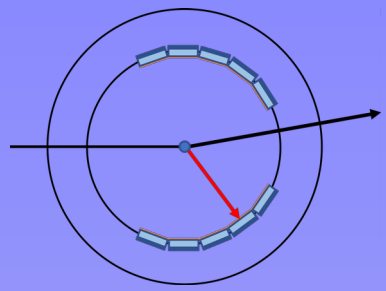
Proton Detection: Recoil Detector

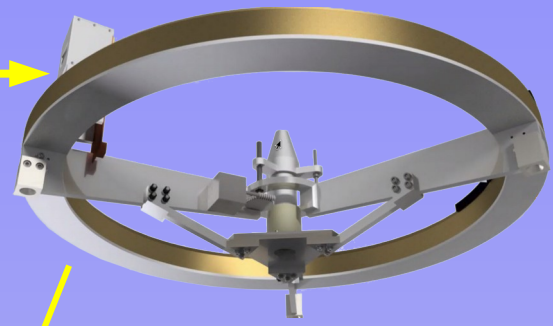
Maik Biroth



Jennifer Geimer

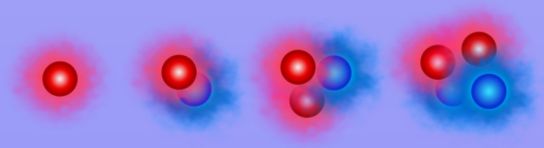






Silicon Strip Detector + Scintillation Detector

detection of low-energetic recoil particles

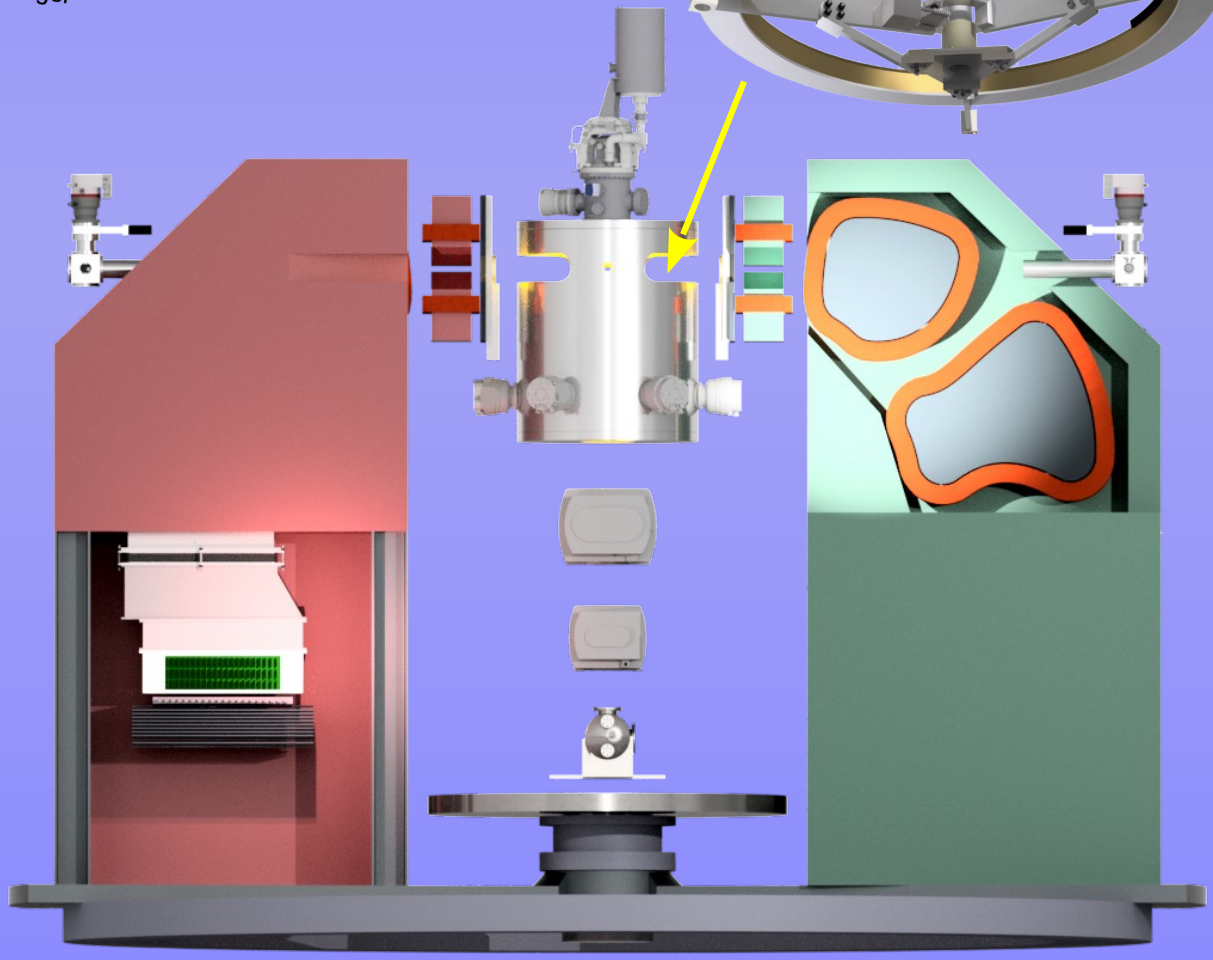


one could do like:

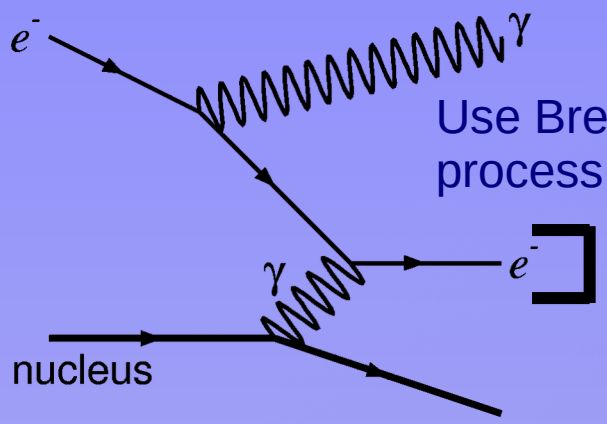
$p(e, e'p)$

$p(e, p)e'$

(not planned)



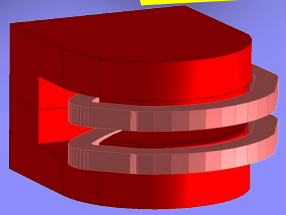
Luminosity monitor / ZDD



Use Bremsstrahlung-process! Møller is out.

$$\mathcal{L} \propto \dot{N}(e_{\text{in}}) \times \rho_{\text{target}} \propto \dot{N}(e'_{\text{det}})$$

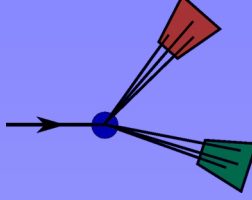
T. Manoussos



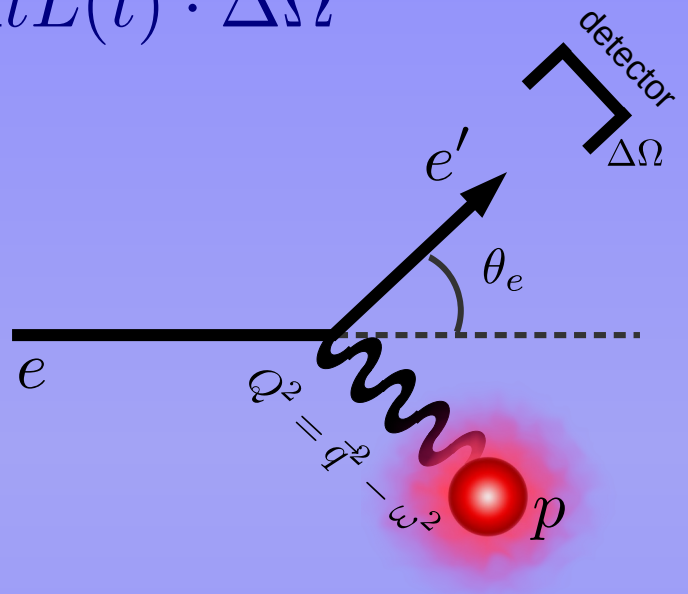
H. Merkel

- special MESA dipole
- also use as Zero-Degree-Detector

Let's do an experiment!



$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{N}{\int \mathrm{d}t L(t) \cdot \Delta\Omega} \cdot \mathrm{corr}$$



$$\tau = Q^2/4M^2$$

$$\epsilon^{-1} = 1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}$$

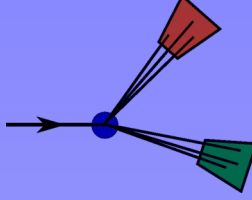
unpolarized cross section, ep-scattering

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_e}\right) = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_e}\right)_{\mathrm{Mott}^*} \cdot \frac{1}{(1+\tau)}\left[G_{\mathrm{E}}^2(Q^2) + \frac{\tau}{\epsilon}G_{\mathrm{M}}^2(Q^2)\right]$$

$G_{\mathrm{E}}^2(Q^2) \leftrightarrow$ charge distribution

$G_{\mathrm{M}}^2(Q^2) \leftrightarrow$ magnetization distribution

Let's do an experiment!



Counts

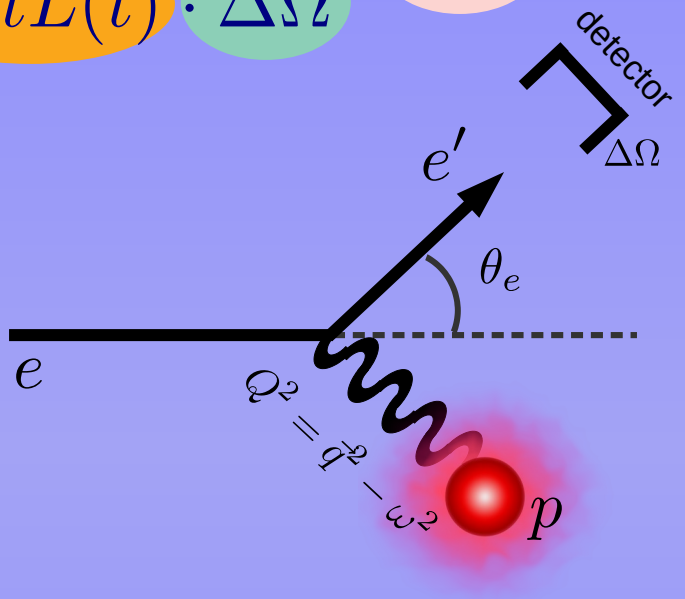
- identify and count elastic events
  - 100% detector efficiency
- background handling
  - 0 background

We'll see, we'll see.

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{N}{\int \mathrm{d}t L(t) \cdot \Delta\Omega} \cdot \mathrm{corr}$$

Luminosity

- current × density
  - target parameters
  - beam current
  - beam overlap
- bremsstrahlung luminosity monitor
- second spectrometer as monitor
  - relative lumi monitoring



Angular acceptance

- point-like target!
- well defined by collimator

$$\tau = Q^2/4M^2$$

$$\epsilon^{-1} = 1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}$$

unpolarized cross section, ep-scattering

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_e}\right) = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_e}\right)_{\mathrm{Mott}^*} \cdot \frac{1}{(1+\tau)}\left[G_\mathrm{E}^2(Q^2) + \frac{\tau}{\epsilon}G_\mathrm{M}^2(Q^2)\right]$$

Corrections

- DAQ dead time
- detector efficiency
- radiative corrections
- ...

$G_\mathrm{E}^2(Q^2) \leftrightarrow$ charge distribution

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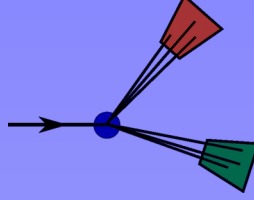
Let's do an experiment!



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$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{N}{\int \mathrm{d}t L(t) \cdot \Delta\Omega} \cdot \mathrm{corr}$$

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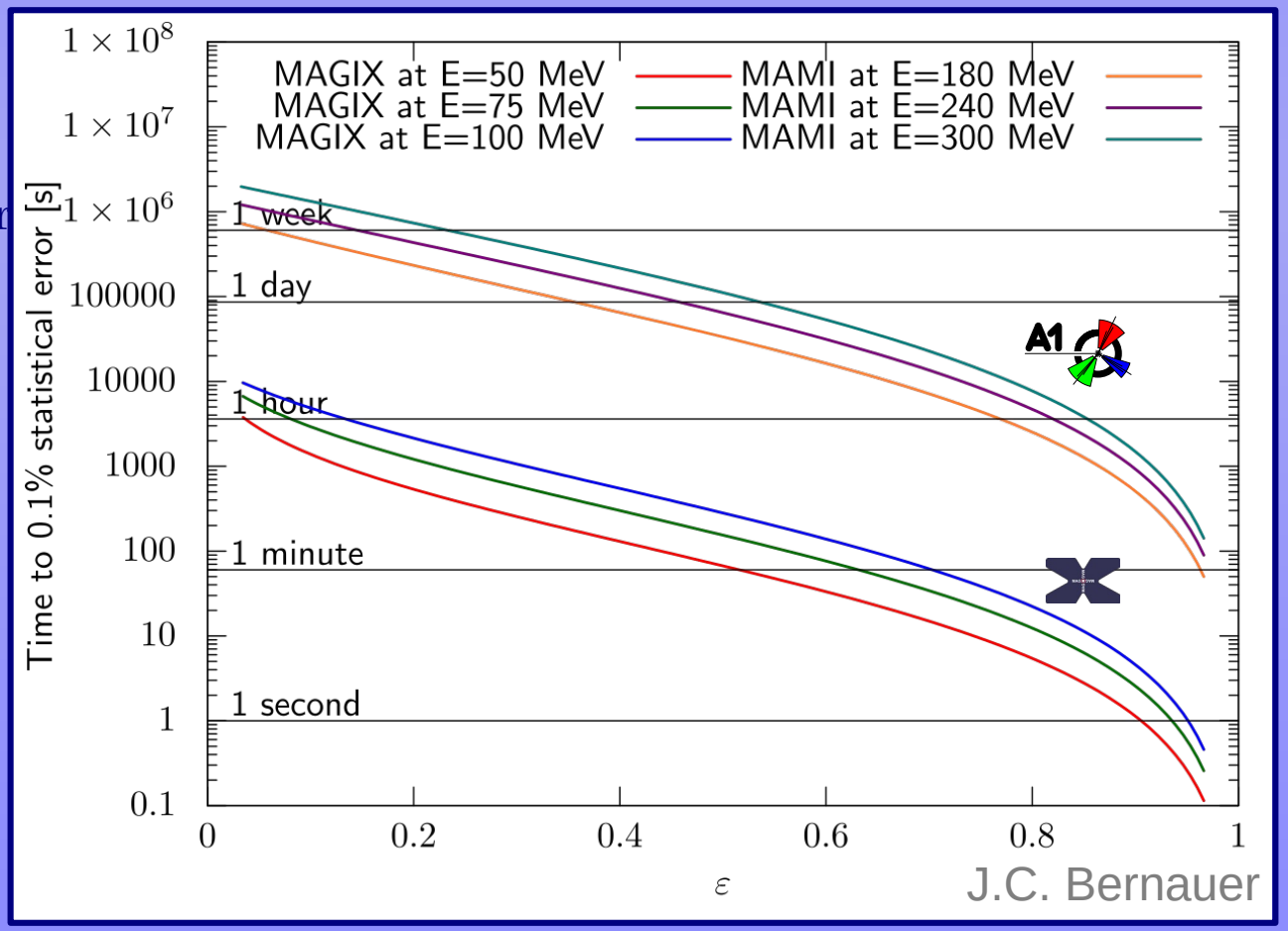
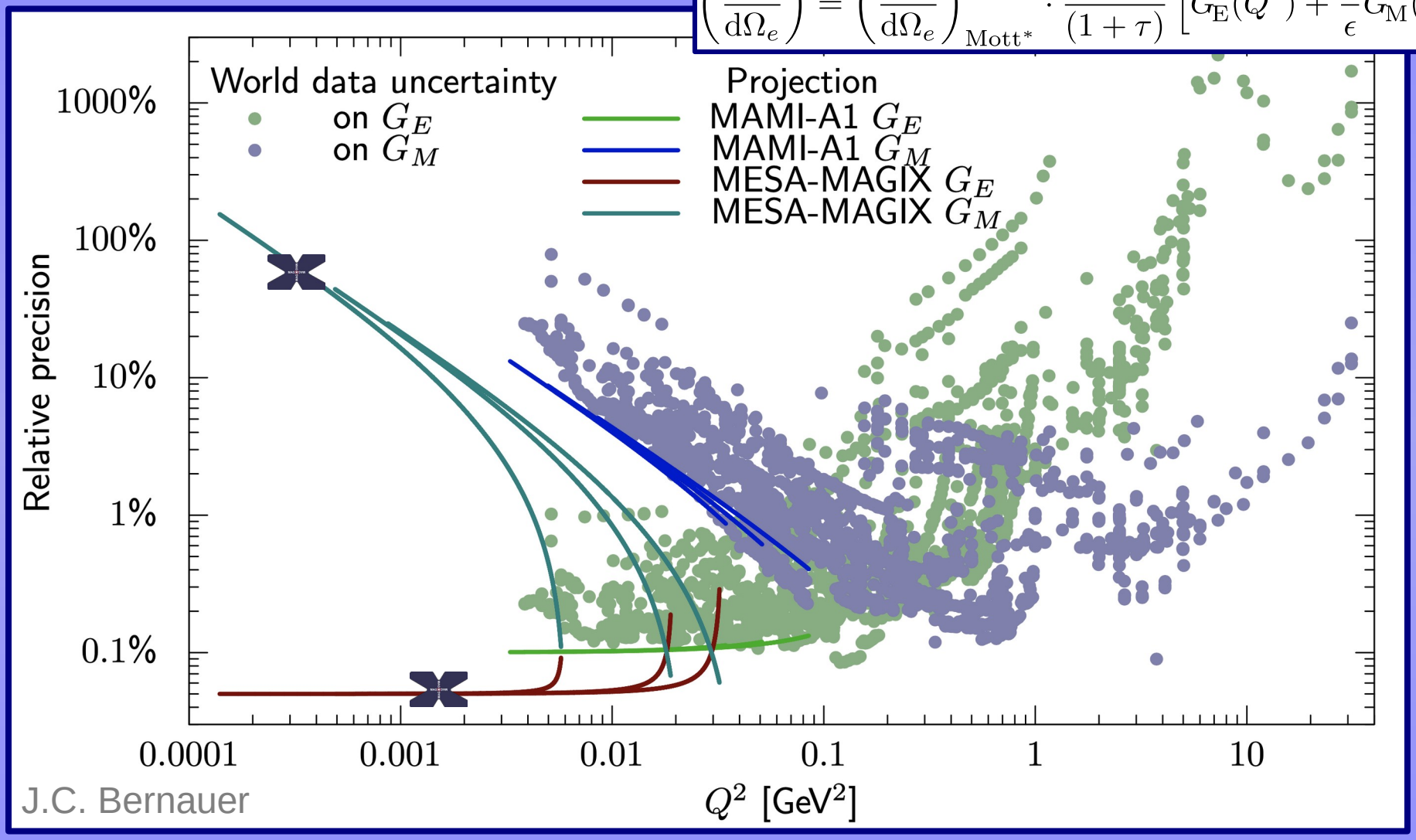


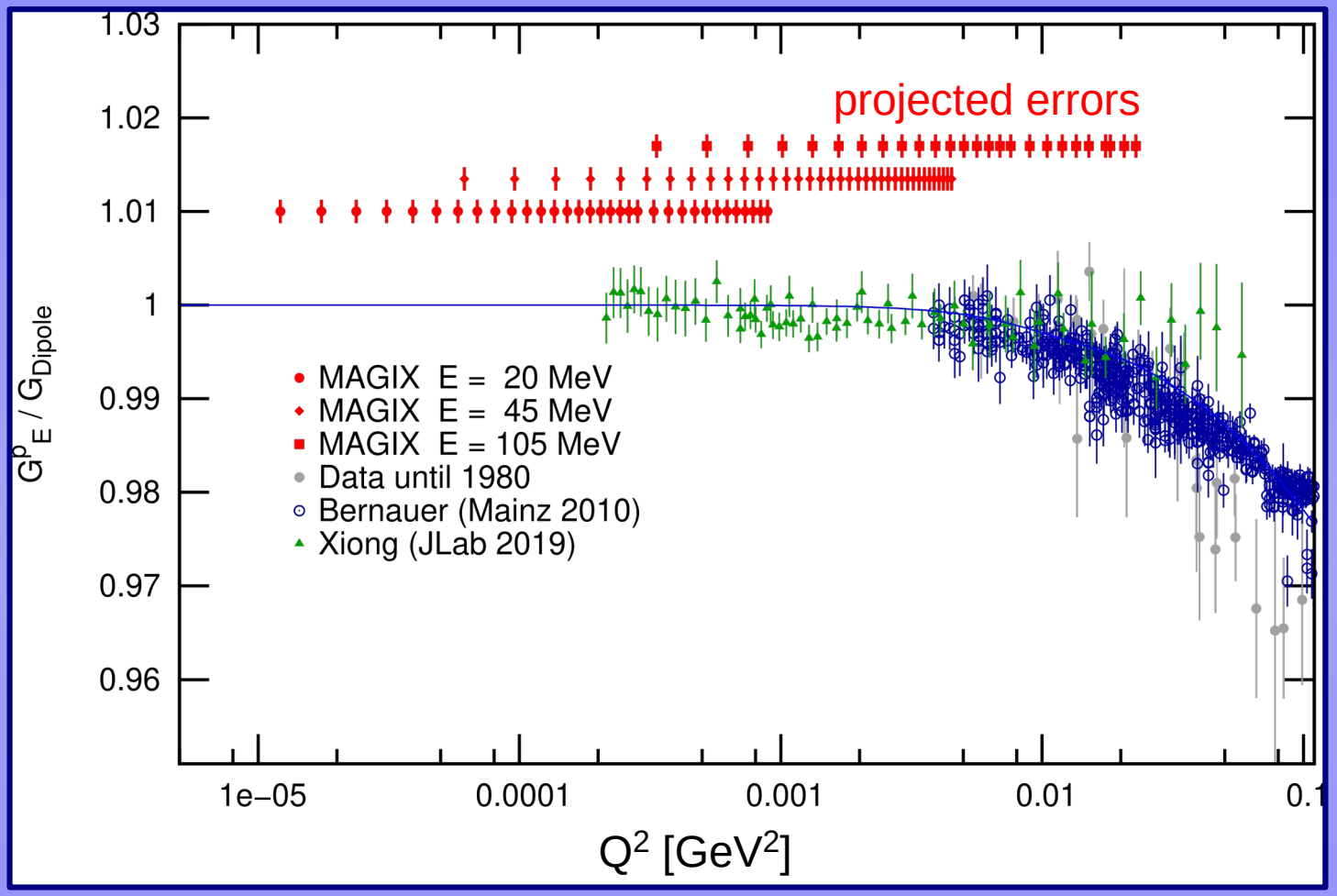
What can we reach?

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_e}\right) = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_e}\right)_{\mathrm{Mott}^*} \cdot \frac{1}{(1+\tau)}\left[G_{\mathrm{E}}^2(Q^2) + \frac{\tau}{\epsilon}G_{\mathrm{M}}^2(Q^2)\right]$$



The world cross section data sensitivity to G_E and G_M. The uncertainty of the cross section is mapped to the respective form factor, assuming the other one fixed. As can be seen, at large Q^2, the data is mainly sensitive to G_M, while at low Q^2, G_E is more precisely extracted. (The PRad data is omitted, as only sensitive to G_E)

Electric form factor at MAGIX



- Coverage from **$Q^2 = 1 \cdot 10^{-5}$ to 0.03 GeV^2** $\Rightarrow$ **proton radius!**
- Dominated by systematic error
  - Windowless target, negligible background, high resolution, high efficiency, ...

H. Merkel

Proton radii experiment at MESA

elastic electron-proton scattering at MAGIX

Sören Schlimme
Institute for Nuclear Physics
Johannes Gutenberg University Mainz

PREN2022 Convention:

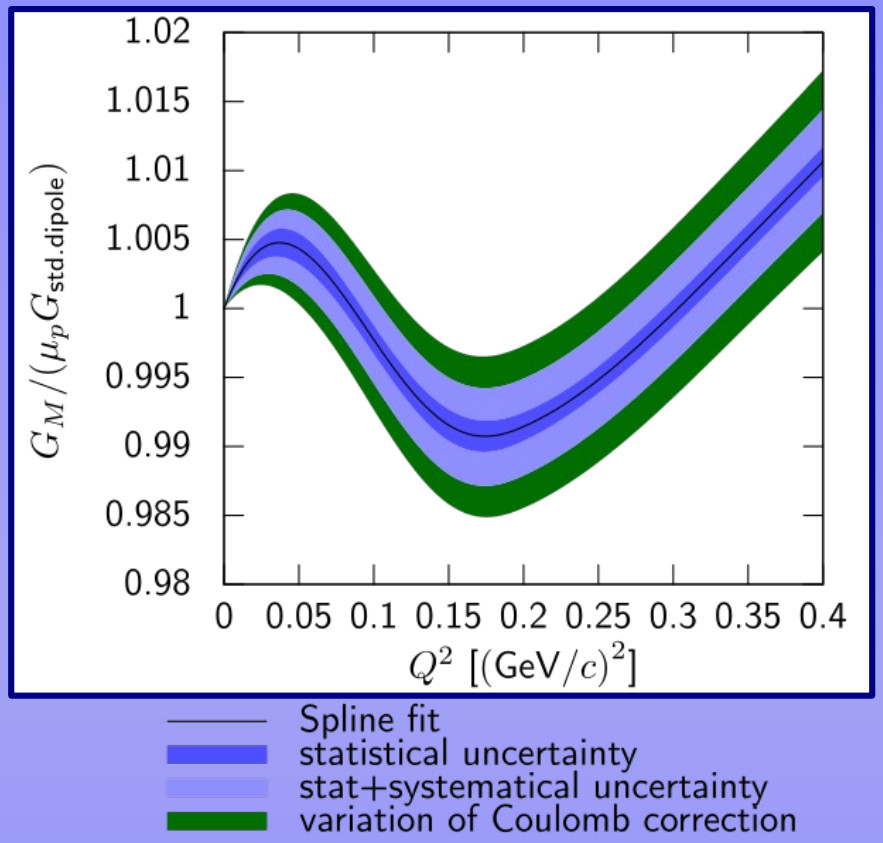
International STRONG-2020 Workshop on the Proton Charge Radius and related topics

June 20-23, 2022, Paris, France

Cluster of Excellence PRISMA+

- Jet Target
- MESA accelerator
- MAGIX Spectrometer Setup
- Proton Form Factor Measurements

Magnetic FF and 'magnetic radius'



The magnetic form factor G_M deviates from earlier measurements. This may be related to the normalization at $Q^2 \to 0$ ignoring the wiggle seen by this experiment.

$$\langle r^2_{E/M} \rangle = -\frac{6\hbar^2}{G_{E/M}(0)} \left. \frac{\mathrm{d}G_{E/M}}{\mathrm{d}Q^2} \right|_{Q^2=0}$$

$$\langle r_E^2 \rangle^{1/2} = 0.879(5)_{\text{stat}}(4)_{\text{syst}}(2)_{\text{model}}(4)_{\text{group}} \text{ fm},$$

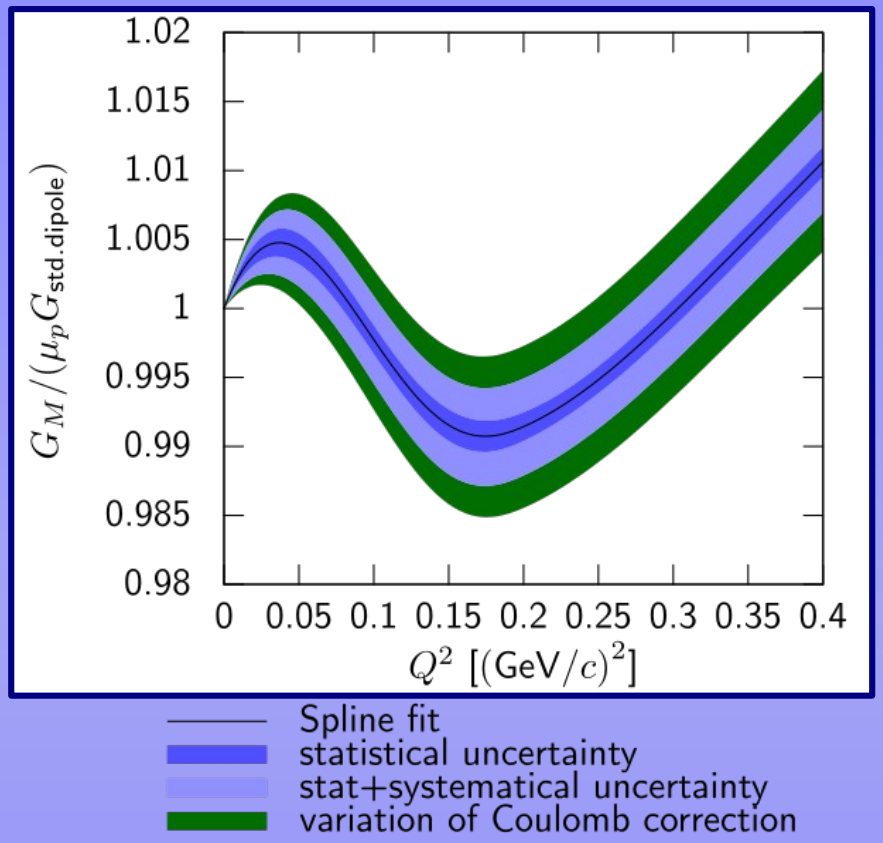
$$\langle r_M^2 \rangle^{1/2} = 0.777(13)_{\text{stat}}(9)_{\text{syst}}(5)_{\text{model}}(2)_{\text{group}} \text{ fm}.$$

G_M is also important for the Zemach radius, another connection to atomic physics:

$$r_Z = -\frac{4}{\pi} \int_0^\infty \frac{\mathrm{d}Q}{Q^2} \left(\frac{1}{\mu_p} G_E(Q^2) G_M(Q^2) - 1 \right)$$

J.C. Bernauer

Magnetic FF and 'magnetic radius'



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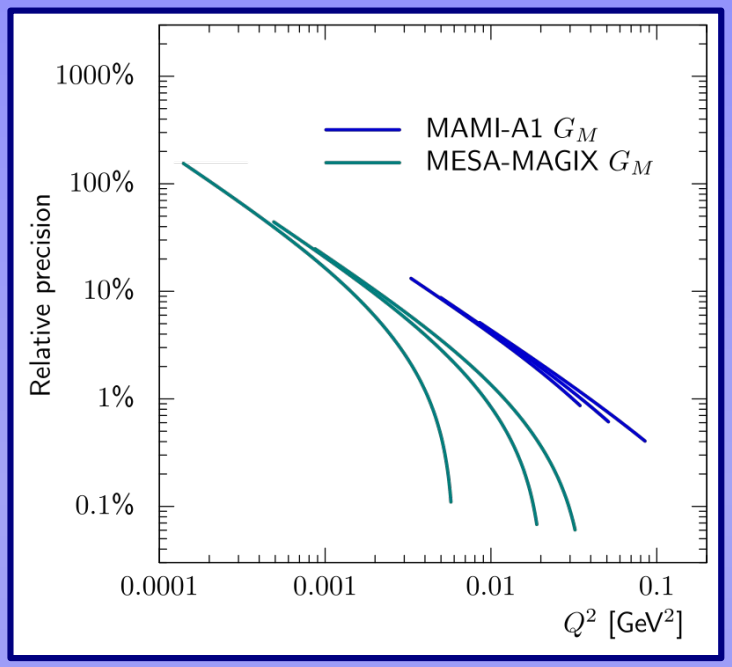
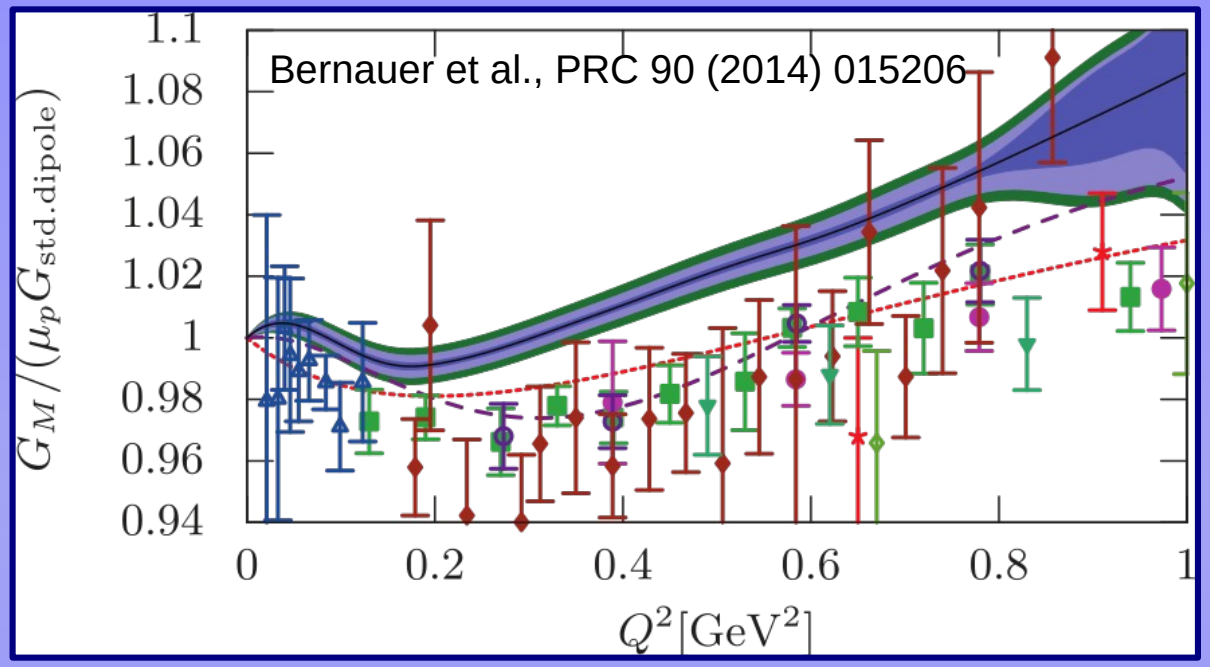
Problemo: at small Q^2, τ is small; insensitive on G_M unless ϵ small...

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_e} \right) = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_e} \right)_{\text{Mott}} \cdot \frac{1}{(1+\tau)} \left[G^2_{\text{E}}(Q^2) + \frac{\tau}{\epsilon} G^2_{\text{M}}(Q^2) \right]$$

Backward angles at small energies → **MAGIX at MESA.**

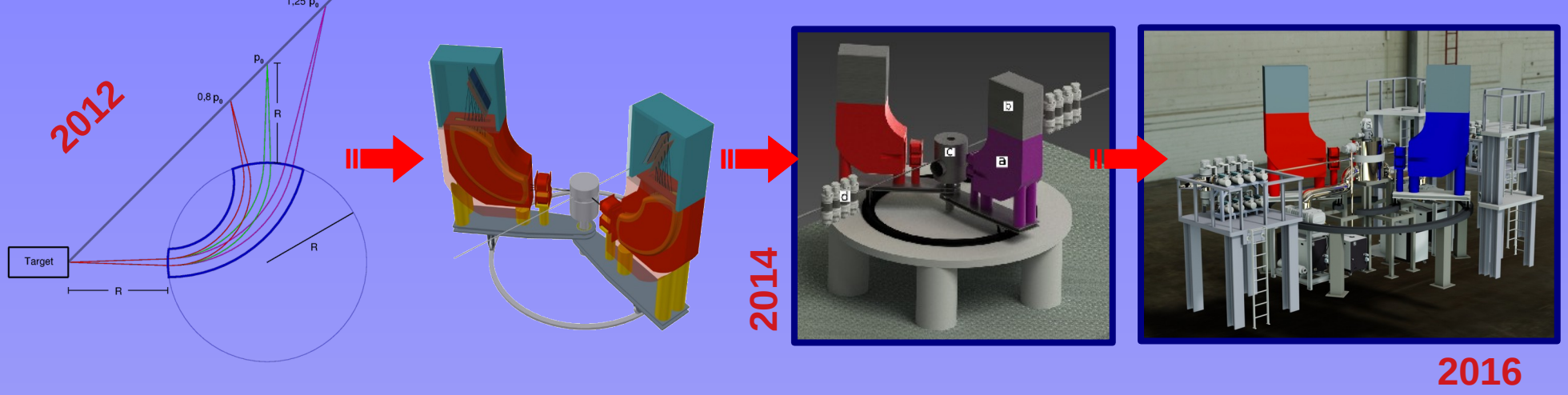
Magnetic FF and 'magnetic radius'



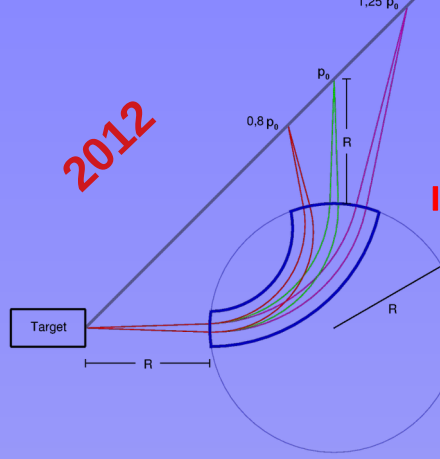


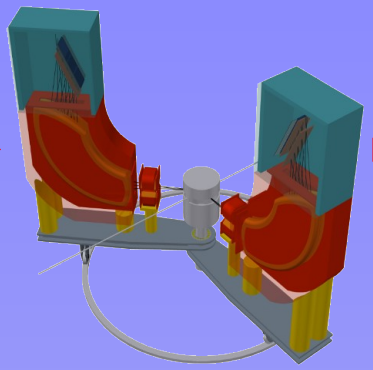
Significant improvement of existing data is possible

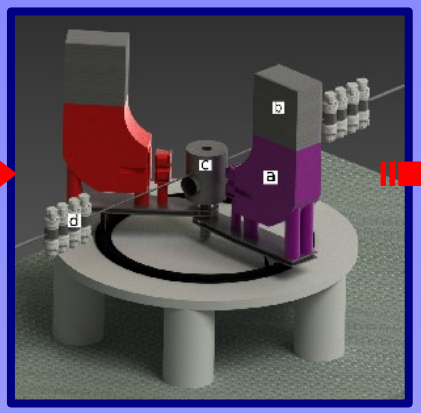
at low momentum transfers

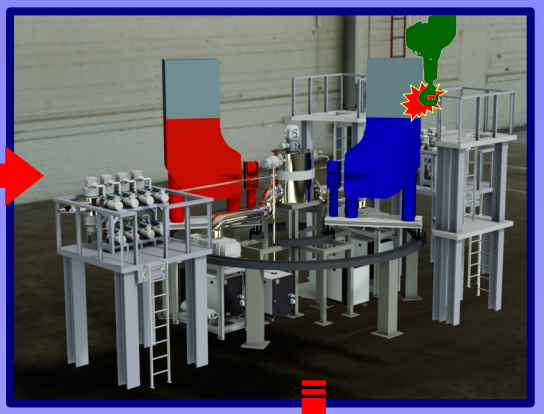


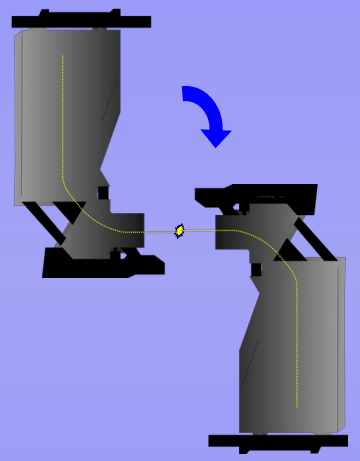
PAST, PRESENT, AND OUTLOOK





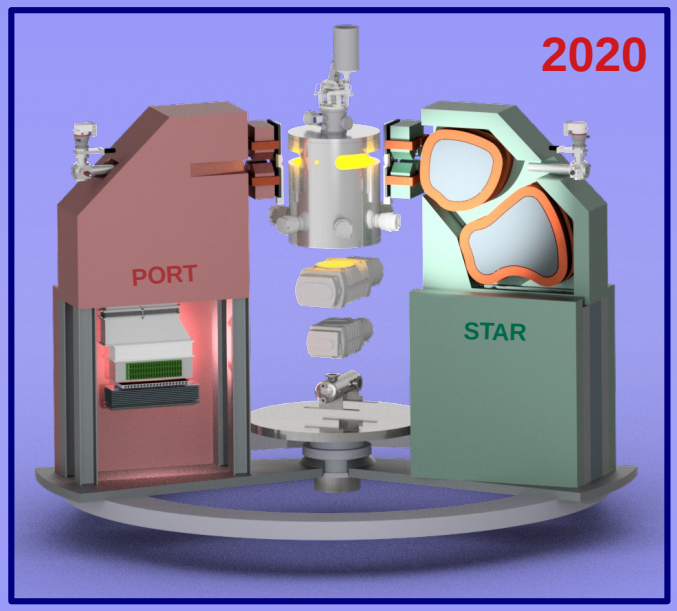


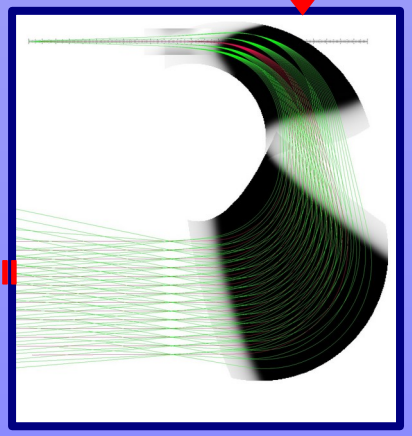


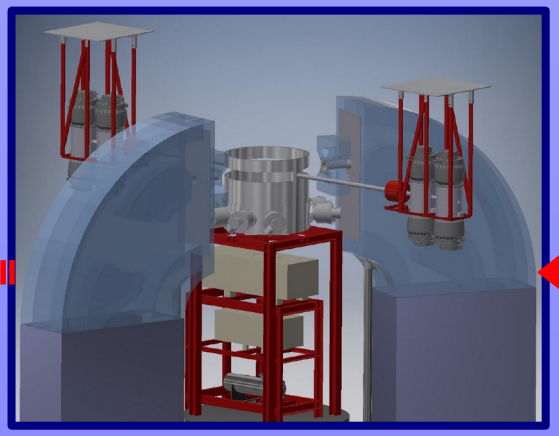


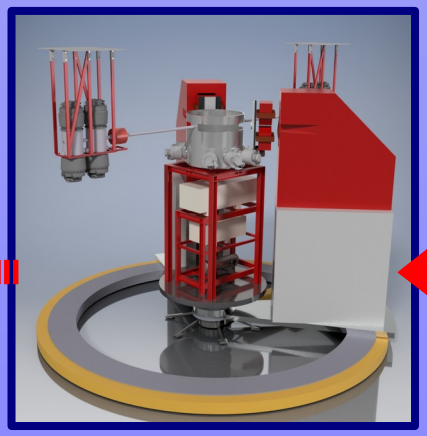
PAST, PRESENT, AND OUTLOOK

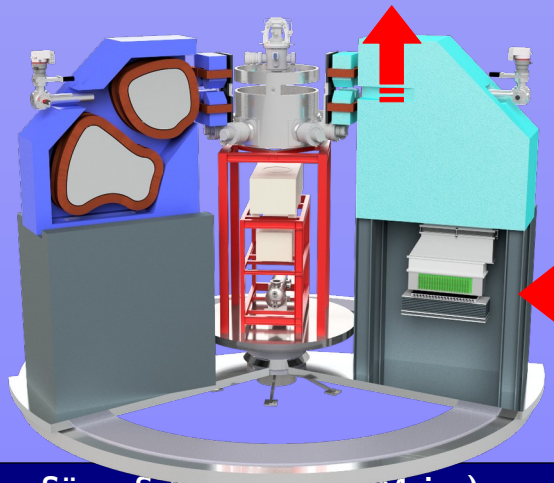
everybody will love the green one

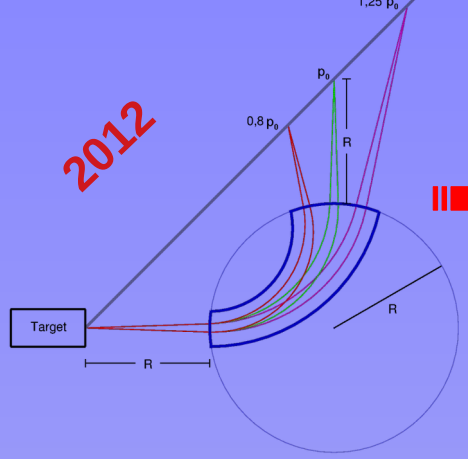


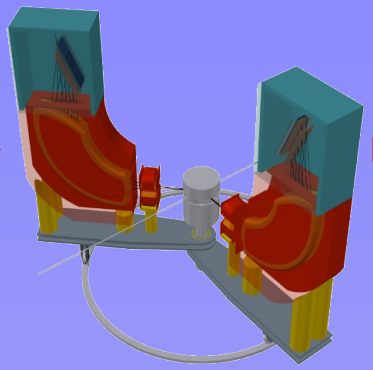


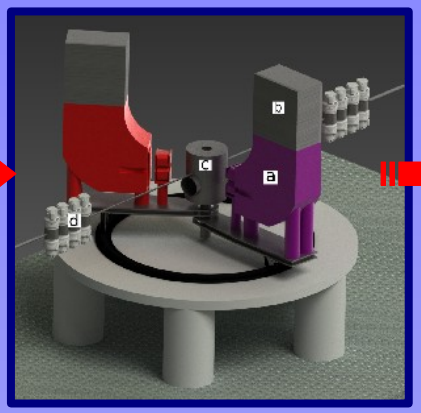


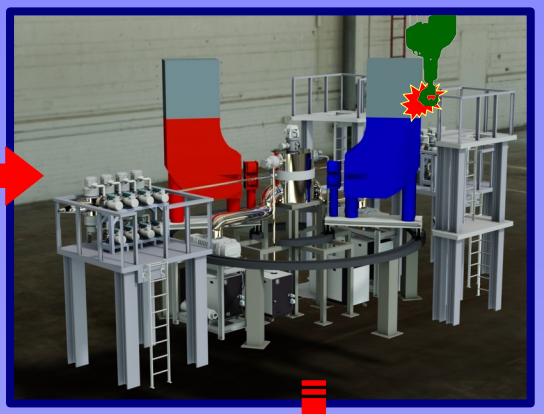


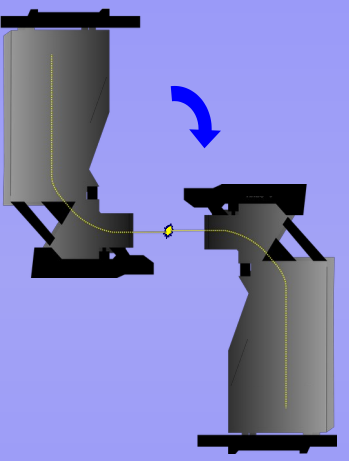


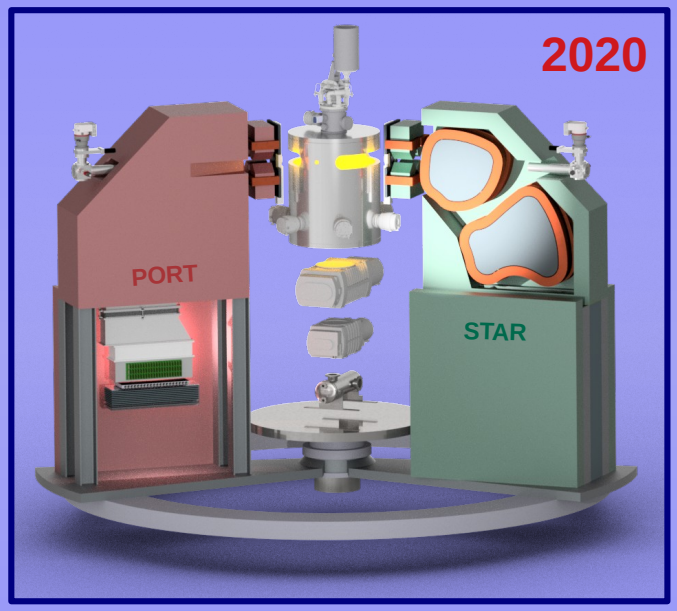












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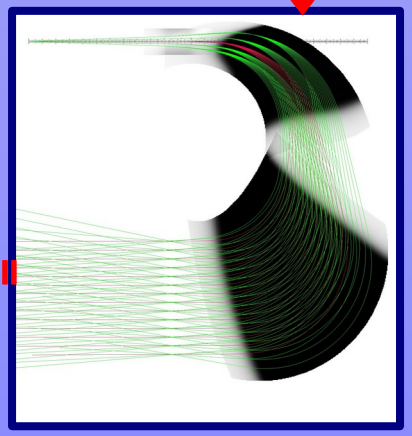
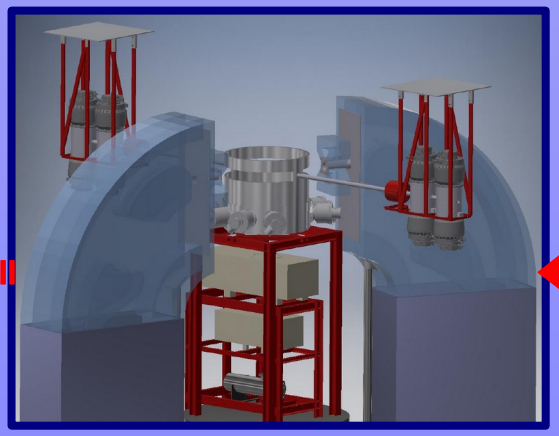
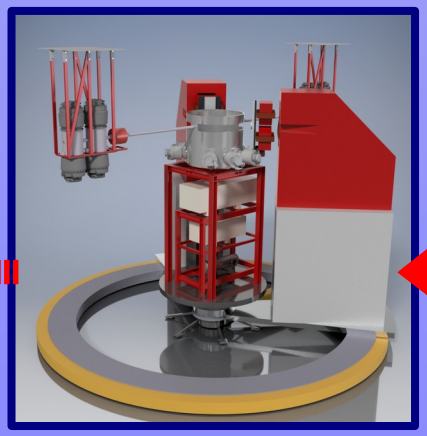
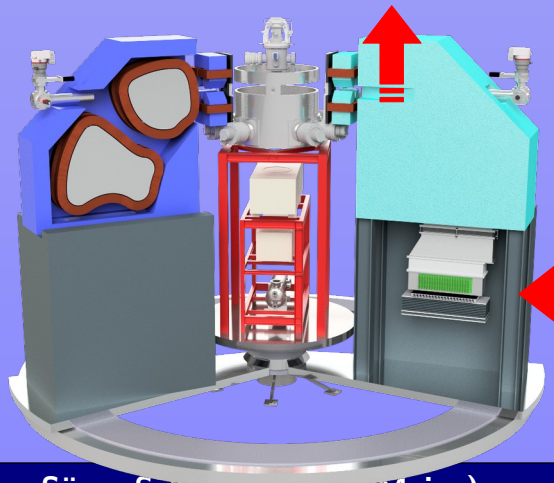
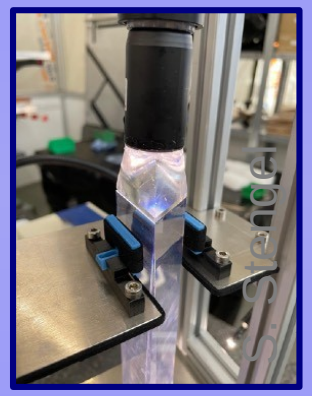
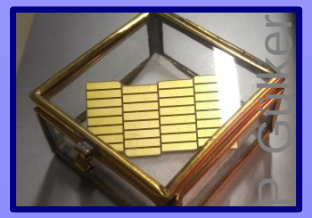










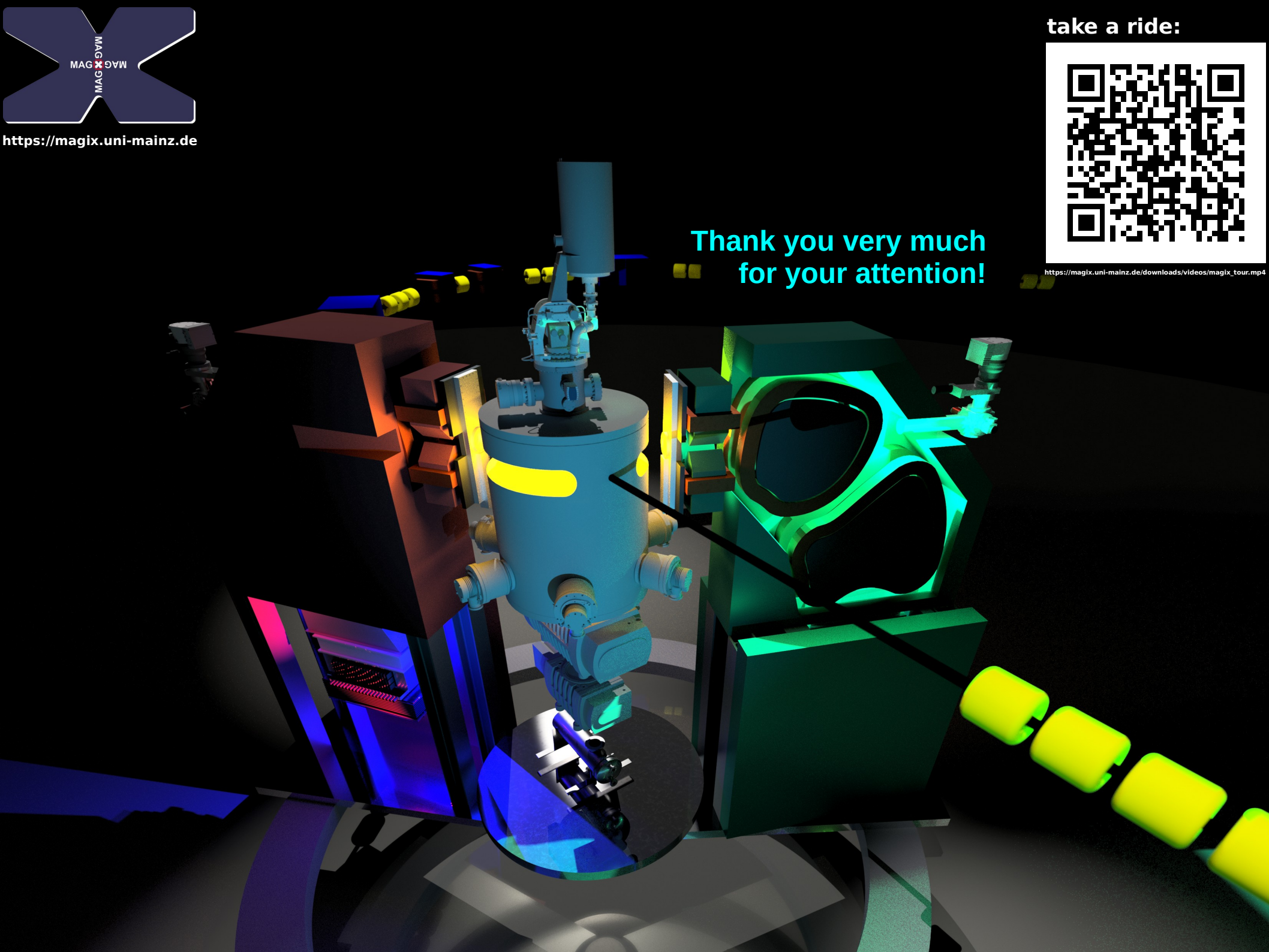


2022 (end)	experimental halls ready
2023 (Mar 12)	delivery of StarPort
then	spectrometer assembly
then	detector assembly, ...
2023 (early)	start MESA assembly
2y later	first beam for experiment

Calibration → ^{12}C transition FF → Dark Photon → Proton FFs or so :)

Summary

- **Proton radius puzzle (2022): data still not consistent...**
  - search for explanation
    - call for dedicated data
      - low-Q^2 electron scattering data with reduced background
- **MESA: a new electron accelerator for precision physics**
  - EB mode for P2 and DarkMESA
    - 150 µA, 155 MeV
  - ERL mode for MAGIX
    - up to 10000 µA, 20 - 105 MeV
- **MAGIX: a multi-purpose electron scattering experiment**
  - windowless gas-jet target, H, D, ^{3}He, ^{4}He, ..., Xe
  - 2 × high resolution magnetic spectrometers (**StarPort**)
  - Objectives:
    - Dark Sector Searches
    - Few-Body Systems
    - Nuclear Astrophysics
    - Hadron Structure
- **Proton radius/radii experiment**
  - electric and magnetic FF measurement
    - minimized background, down to very low momentum transfers
    - unpolarized cross section measurements
    - FF separation, proton radii determination
      - high statistics, errors dominated by systematic error
        - radiative corrections and the like :)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for your attention!